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The Measurement Of Synchronous Impedance

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THE MEASUREMENT OF SYNCHRONOUS IMPEDANCE

BY

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WILBERT EUGENE UNDERWOOD

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

HERBERT COLES STEPHENS and WILBERT EUGENE UNDERWOOD

ENTITLED MEASUREMENT OF SYNCHRONOUS IMPEDANCE

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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THE MEASUREMENT OF SYNCHRONOUS IMPEDANCE.

INTRODUCTION:

The designer of dynamo electric machinery must predetermine as far as possible, the operation of his machine and the efficiency of the machine depends greatly on the precision with which its operation can be estimated beforehand. Knowledge of voltage regulation is much to be desired in the operation of electrical machinery and the calculation of regulation on alternators has always been the despair of the designer. Theory which does not accord with practice is useless and it must be admitted that the theory of regulation is not entirely logical, nor does it concur with practice. A factor of vital importance in the reckoning of regulation is synchronous impedance and the one great difficulty lies in the assignment of a proper value to this quantity. A satisfactory method of measuring synchronous impedance under working conditions has never been devised and the designer is forced to work on assumptions. Thus it is evident that a precise method of measuring synchronous impedance would be of inestimable benefit to the designer.

Authors and designers are quite unanimous in assuming synchronous impedance to be a constant quantity, or very nearly so, and almost all predeterminations of regulation are made on this assumption.

The object of this thesis is to investigate the soundness of the assumption that synchronous impedance is a constant quantity. The investigation is made by determining experimentally the value of this quantity under various conditions of loading. An attempt is made to analyse the effect of different factors on synchronous impedance, namely, variable armature current under constant field excitation; variable armature current under constant terminal pressure; and variable power factor. As an aid in the Study of synchronous impedance, simultaneous values of the armature working impedance are found.

DEFINITION:

The synchronous impedance of an alternator, for a given armature current, a given field excitation and normal speed, may be defined as an impedance, which, if inserted in a separate external circuit, would permit the same flow of current, with an impressed pressure equal to the open circuit voltage of the alternator at the same speed. Synchronous impedance is an imaginary fictitious quantity and has not an actual physical existance as an impedance. It is a factor, however, of considerable interest because it so intimately concerns the regulation of an alternator.

GENERAL THEORY OF THE METHOD OF MEASUREMENT EMPLOYED.

If an alternator be run at normal speed and excited to give a definite pressure upon open circuit, and an inductive load be thrown upon it, maintaining the same speed and excitation, the pressure at the armature terminals will be less than the open circuit pressure due to numerous reactions within the machine . This drop may be accounted for in part by the ohmic resistance and the reactance of self induction in the armature windings. A third factor is armature reactions, a composite quantity made up of various factors resulting in a deficit of voltage at the armature terminals. The armature resistance drop may be represented by a vector in phase with the current and the inductive drop by a vector in quadrature with the current. These two vectors may be combined into a third, known as impedance drop. The two components, resistance and inductance, form a resultant impedance which may be designated as the working impedance of the armature. Assuming that the iron losses of the armature are supplied by the field current entirely, the armature reactions may be said to represent a drop or absence of terminal volts, having no component in phase with the current. This armature interference or drop may be graphically represented by a vector in quadrature with the current.

GRAPHICAL CONSTRUCTION:

In the accompanying diagram fig. 0. p. 4 , let I represent the current and E, the terminal pressure, when the current I, lagging by the angle Θ is flowing. Then the armature resistance and inductance drops may be represented by I R and $I\omega L$,

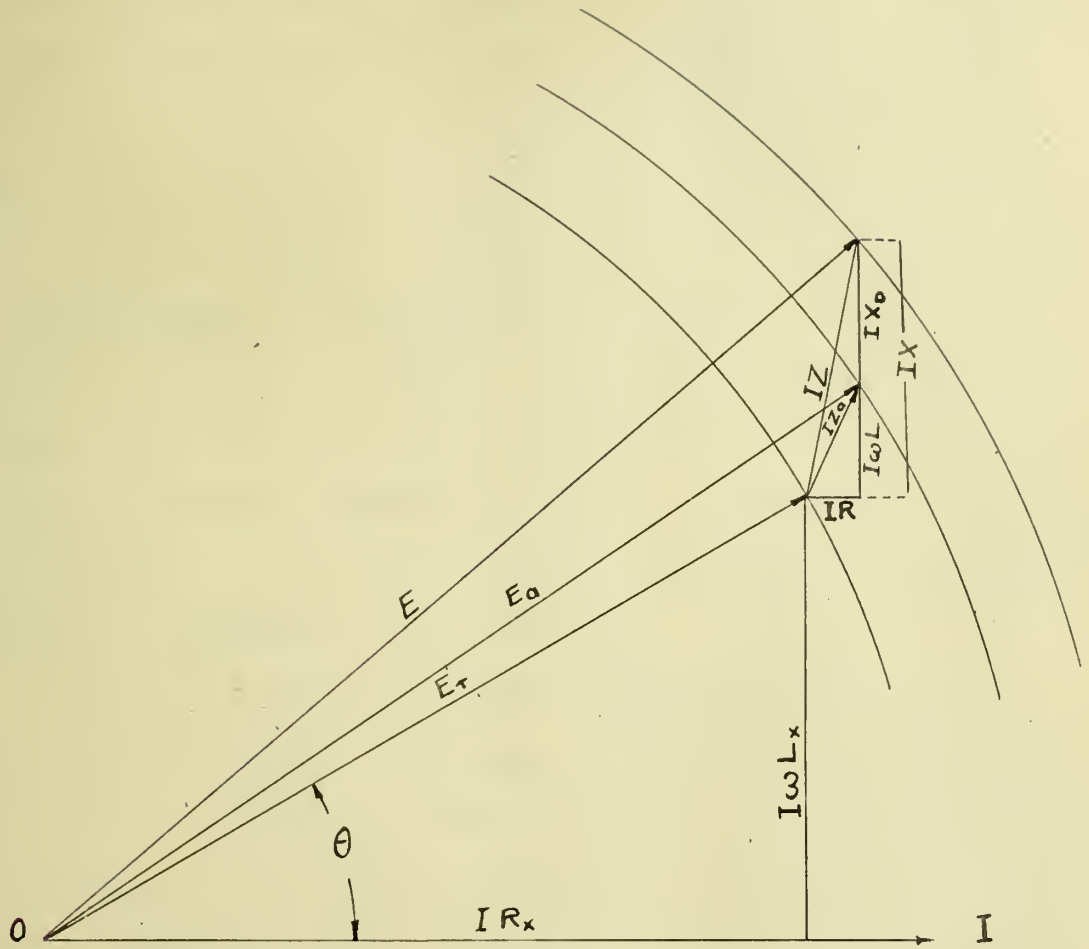


FIG. 0.

respectively. The vector IZ_a then represents the armature working impedance drop, and the vector E_a, the total pressure generated within the armature under the load condition. E_a, thus determined, is the vector sum of the resistance and reactance drops of the external circuit, $I R_x$ and $I \omega L_x$, and the resistance and reactance drop within the armature $I R$ and $I \omega L$ respectively. If E_a be measured by use of a search coil placed upon the armature, and its value represented to the proper scale, an arc may be struck from O as a center intersecting a perpendicular erected from the terminus of I R, as defined by E_T, Θ and the values I and R of the armature, such that the distance, from this intersection to the terminus of E_T, is the working impedance drop of the armature, IZ_a. From the value IZ_a, the working impedance may be readily determined by dividing by the current.

If the open circuit pressure E, for the same value of field current and speed, be known, and a similar arc struck with a radius equal to the value of E, its intersection with the perpendicular, as previously defined, determines the length of the vector I Z, the synchronous impedance drop of the machine. The vector IX_o, that part of IX, the synchronous reactance drop above $I\omega L$, represents the armature interference volts, or deficit of volts, due to armature reactions. I Z is the vector summation of all pressure present on open circuit, but unavailable at the armature terminals because of the internal reactions of the armature underload. I Z divided by I is the value of synchronous impedance for the particular conditions as defined. The above described method of determining synchronous impedance may be termed the E. M. F. Method. It is employed in the

determination of both synchronous and working impedance in the following tests.

MEASUREMENT OF SYNCHRONOUS IMPEDANCE BY THE SHORT CIRCUIT METHOD.

The usual method of measuring synchronous impedance is by the short circuit test, which consists in running the alternator at normal speed with its armature short circuited thru an ammeter and leads of negligible resistance and inductance. The field is excited to give various armature currents. The open circuit, terminal pressure for the same speed is then taken, for the values of field current corresponding to the various armature currents. The sychronous impedance for any load current is then obtained by dividing the open circuit pressure at the field current corresponding to the given armature current by that armature current that is $Z_{SYN.} = E/I$. E is the open circuit voltage or the voltage that would be generated in the armature were it not for armature reactions. The actual generated voltage in the armature, which will be designated by E_a, is less than the open circuit voltage because of a deficit of voltage due to armature reactions. The actual voltage at the terminals of the machine under short circuit, which will be designated by E_s, is less than the actual generated volts E_a, by an amount corresponding to the armature impedance drop.

The horizontal line A B, fig 1, p.7 represents the armature current; I R, the drop in phase with the current; and E, the open circuit pressure for a field current corresponding to the armature current; E_s, the

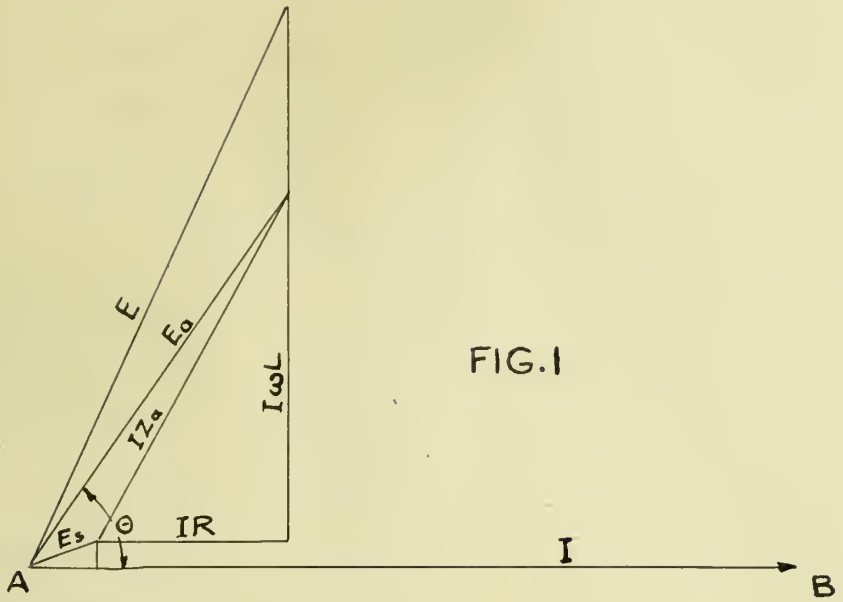


FIG. 1

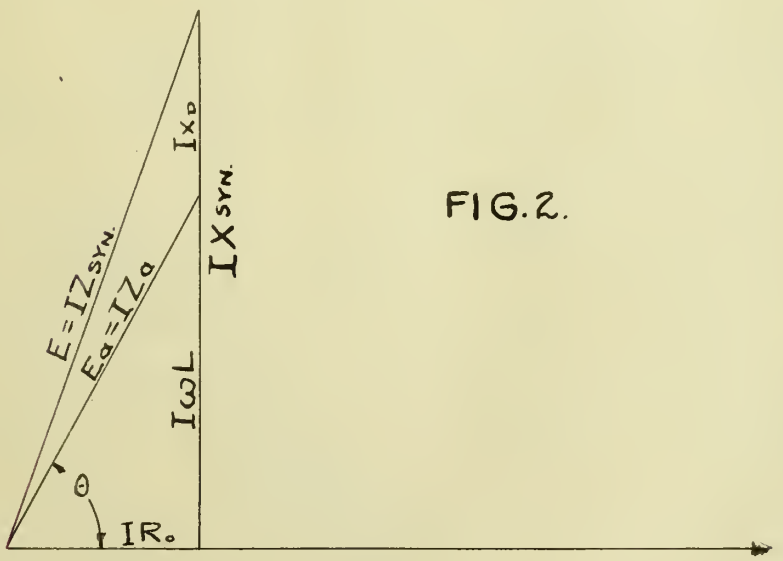


FIG. 2.

short circuit terminal pressure; and E_a, the actual armature generated volts. Since the pressure E_s. representing the drops (I_r and I_x) in the ammeter and leads is small, this factor may be omitted from the consideration so that the diagram will assume the form of fig I, in which $E=I\ Z$, the synchronous impedance, and $E_a = I\ Z_a$, the impedance of the armature. $I\ R_a$ = armature resistance drop, $I\omega L$ = the armature inductance drop, and $I x_a$, a deficit of voltage, accounted for by armature reactions. It has been assumed in the vector representation that the armature iron losses are supplied by the field current entirely; therefore the synchronous impedance may be considered as having no component in phase with the current, except the armature resistance. Ix, the arithmetical sum of $I\omega L$ and $I x_a$, represents the synchronous reactance component. Θ represents the angle of lag of the armature current behind the actual generated voltage E_a.

From theoretical considerations, in view of the fact that the I R drop is negligible as compared with the inductance drop for the ordinary armature, and the angle of current lag is almost 90 degrees, the effect of armature reactions would be expected to be large especially at low field excitation. Likewise the iron of the armature core under short circuit conditions is worked at a low density so that the coefficient of self induction of the armature winding would naturally be high on account of the high value of permeability, thus causing a large inductance especially on small loads. As a result a large value of synchronous impedance might be expected on small loads.

DISCUSSION.

The short circuit method is commendable for one reason in particular, that it affords an approximate method of determining synchronous impedance requiring but very little power. It is especially advantageous for determining approximately the regulation of an alternator in a shop test where facilities are not at hand for loading the machine up to its normal capacity and where a lead test would involve a considerable expense. For this reason it has been and will continue to be of considerable use to the designer of certain types of machines.

Dr. Behn Eschenburg of the Oerlikon works, who was a pioneer in the study of the regulation of machines, is credited with suggesting this method of determining the apparent or synchronous impedance of an alternator. His tests were conducted upon various machines, some of them of the inductor type. Using the synchronous impedance as obtained by these tests in connection with the electro-motive force or pessimistic method, the regulation of inductor alternators can be quite closely determined.

B. A. Behrend in his paper presented before the 177th meeting of the American Institute of ElEctrical Engineers, says of the method; "The theory superficially considered appears very plausible but it is evident that it throws together without explanation or justification, the armature reactions and self inductive effects produced by the local field in the armature." The chief objection lies however, in the fact that the method takes no account of the power factor of the

circuit, which plays a very important part in the armature drop as may be seen by a study of the synchronous impedance under variable power factor in the succeeding pages.

For the sake of comparison, measurements of synchronous impedance by the short circuit method were made during the tests conducted and the results compared with those obtained by measurement under actual load conditions.

RESISTANCE BALANCE:

Another method has been suggested which for lack of a better name might be termed the balance method. This test consists in balancing the working impedance of the machine against an external resistance in the circuit. First the armature is short circuited producing a current I, for a certain field excitation. If resistance then be inserted in the external circuit it is assumed from the following mathematical discussion that the external resistance will be nearly equal to the synchronous impedance when the current flowing I_2 , is equal to .7 I_1.

Let the impedance of the armature be $(r + jx)$. Considering the resistance as negligible the armature impedance will be equal to jx and $I_1 x = E$

When a resistance R, equal to X, is inserted in the external circuit for the same field excitation,

$$I_2 (R + jx) = E$$

since $R = x$, $E = \sqrt{2}\, I_2 x = 1.41 I_2 x$

$$E = 1.41\, I_2 x = I_1 x$$

$$1.41\, I_2 = I_1$$

$$I_2 = .709\, I_1$$

The synchronous impedance by this method admittedly neglects the armature resistance but was intended as an advance over the short circuit method. The first fallacy in the theory is the assumption that synchronous impedance is identical with the working impedance of the armature. Secondly, the important factor of armature reactions is ignored entirely. Hence this method is more unjustifiable than the short circuit test.

INDUCTANCE BALANCE:

The balance might be obtained with either resistance or inductance in the external circuit. If inductance were used a mathematical solution similar to the foregoing would show the balance to be obtained when one half the short circuit current is flowing. This method is open to all the objections of the resistance balance method and in addition introduces a power factor so low as to make results obtained from it almost useless.

OPERATION:

The resistance method was tried on the 120 K.W. Westinghouse Alternator. The machine was maintained at synchronous speed and the short circuit current found at a given field excitation. A rheostat was then inserted in the external circuit and resistance cut in until seven tenths of the short circuit current was flowing, the field excitation being the same.

The resistance of the portion of the rheostat in the circuit was then found. The synchronous impedance of the alternator is then equal to this resistance according to the theory which however, is sadly in error, as has been pointed out.

(The results of this test may be found in Table VII-p 44.)

VARIATION OF IMPEDANCE WITH ARMATURE CURRENT.

CONSTANT TERMINAL PRESSURE:

Upon non-inductive loads armature reactions would be expected to have a minimum effect, due to the absence of demagnetizing action upon the part of the armature current. As a result the best regulation would be expected under this condition. The synchronous impedance however, will be least at some load of leading power factor when the capacity effect of the leading current just counter balances the inductance of the armature winding, producing a state of resonance in which the resistance is the only quantity existing as an impedance. The synchronous impedance for a constant terminal pressure and variable excitation and armature current upon non-inductive loading, would ordinarily be expected to increase with the current, if the armature self-induction were a constant quantity but only slightly however, because the effect of the armature ampere turns is merely a distorting one and would therefore decrease the available flux only as it changed the air gap reluctance, by changing the length of the path. The assumption of a constant armature inductance is not corrobrated by experiment. The inductance decreases with load, the reverse of the effect of armature reactions. The variation of the synchronous impedance under the above condition would naturally be expected to be small. Without doubt the question which has perplexed the designer of alternating current machines more than any other, is how to determine the inductive drop in the armature. The inductive drop represented by $I\omega L$, constitutes only a part

of the synchronous impedance but it is a variable quantity which can be determined by calculations only very roughly, from the ampere lines per square inch, which will be set up about the armature conductors. These lines which constitute the local leakage flux of the armature windings are of three classes in general, as regards the path they follow; namely, those which surround the end turns of the winding and have no iron in their path; those which surround the part of the conductor imbedded in armature slots and have as their path the armature teeth; and a third set which which pass out thru the air gap and complete their path thru the pole faces. Each of these three classes must be dealt with separately and only rough approximations can be made for the values to be assigned to them,and the effect of power factor is impossible of consideration.

Extensive measurements of the inductance of an armature of the stationary type were made by Edward Heitman in 1901, under various conditions. His measurements were taken by impressing an alternating current of unity power factor upon the armature windings and thus determining the drop. Such measurements were made with the field removed, also with the field in place and unexcited and with the field excited, for various positions of the poles with respect to the armature coils. The results with the exception of those with the field removed showed an inductance considerably greater than the calculated value and varying greatly with the position of the poles with respect to the windings.

In a study of synchronous impedance under various conditions of loading, this factor of self induction in the

armature plays an important part. Although the primary object of the experiments conducted was to obtain the synchronous impedance of the machines under test, measurements were made to determine this other factor under the varying conditions of the test.

THEORETICAL CONSIDERATION OF THE EFFECT OF VARIABLE POWER FACTOR.

For the purpose of studying the synchronous impedance of an alternator under various conditions as to power factor, field excitation, armature current and terminal pressure, attention is here directed to Kapp's diagram as shown on page 16, figure 3. In the construction of this diagram the current I, is represented by the horizontal vector; the terminal pressure by E_T , leading, lagging or in phase with the current; the open circuit pressure for a constant value of field excitation by E , the ohmic resistance drop by IR, in phase with the current; and the reactance drop by I×. As a first consideration in the following discussion the open circuit pressure, field excitation, armature current and speed will be considered as constant and the power factor considered as the variable quantity. With 0 as a center and the pressure 137 volts corresponding to a field excitation of 1.92 amperes, reading.6 Table V p42 . An arc A. B. was struck representing the locus of the open circuit pressure. Then with the corresponding terminal pressure, 110 volts underload, the vector E_T was laid off, leading the current by angle whose cosine equalled the power factor, (about 86%). From the terminus of this vector the I R drop corresponding to the armature current was laid off in phase with the current and a perpendicular erected to its point of intersection with the locus of the open circuit pressure. The vector E was drawn from the point 0 to this intersection. The triangle thus constructed

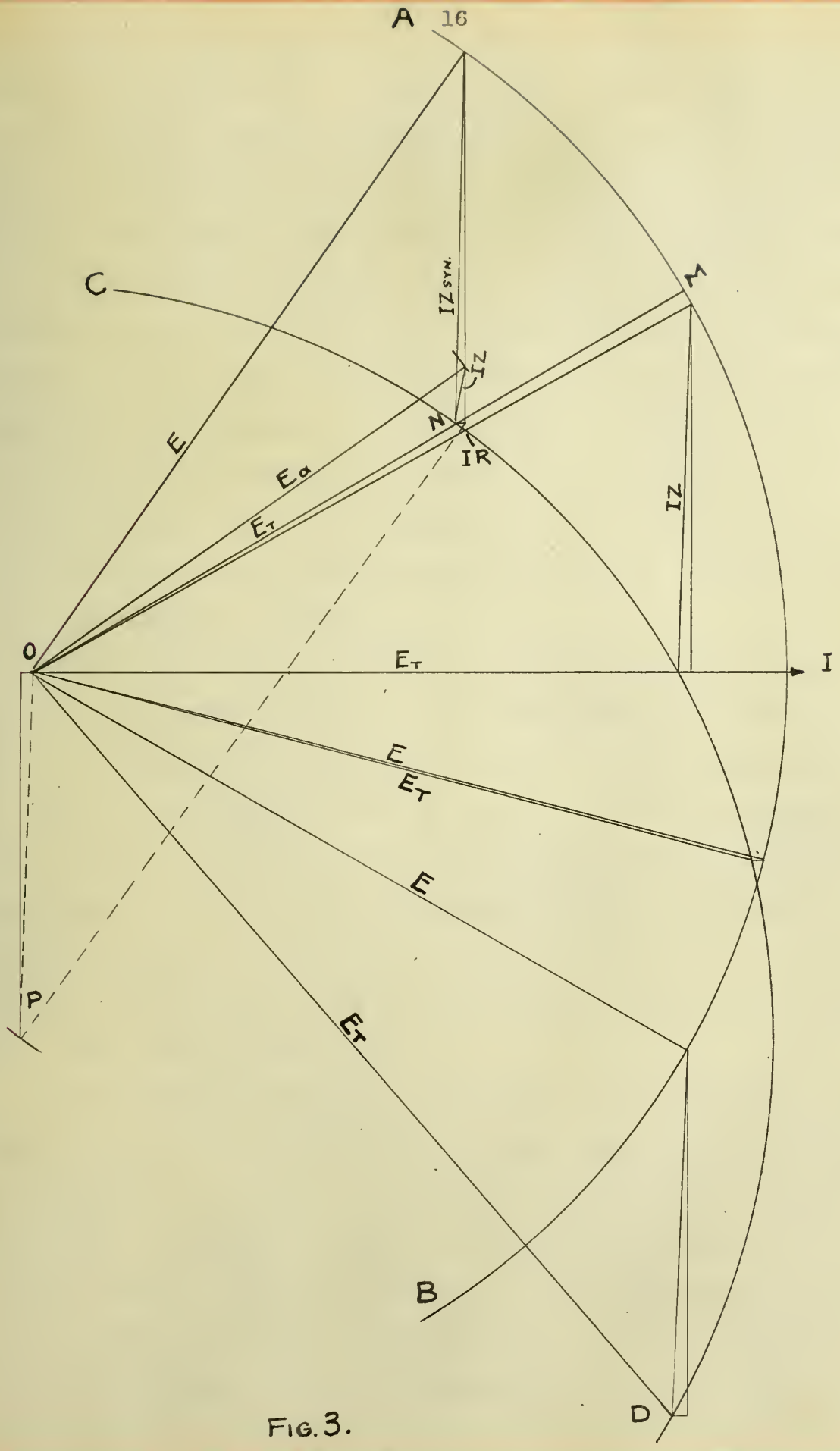


FIG. 3.

represents the terminal pressure by E_T, the synchronous impedance drop by $I Z_{SYN.}$, and the open circuit pressure by E, which is the voltage that would be gemerated in the armature were it not for armature reactions. The open circuit pressure is here considered as representing the vector sum of the terminal pressure and the armature drop. Completing the parallelogram and taking the point P, as a center and P N as a radius, the arc C D was struck representing the locus of the terminal pressure of the machine, for various power factors. The distance between the arcs C D and A B on the vector E_T continued represents the arithmetical difference between open circuit terminal pressure and the terminal pressure for the given armature current.

The vertical distance between the arcs represents the synchronous reactance drop for the given armature current. It will be noted by the diagram that as the current passes from a lagging thru unity to a leading power factor, that armature drop becomes less until a point is reached where the armature reactions on a leading current actually raise the terminal voltage above the open circuit pressure for a given field excitation, thus giving a compounding effect for capacity loads of a large leading power factor.

The resistance component of armature reactions will then, as the current changes from a large angle of lag to a large angle of lead, pass from a large value in one direction thru zero, and assume a value in the opposite direction, becoming a "boost" instead of a drop. In consequence of this change, the synchronous impedance voltage of the armature, which is composed of the two components, resistance and

reactance volts, will assume a value in the opposite direction if this quantity can be said to be directed or a true vector. Thus the synchronous impedance of an alternator may be a factor either assisting the machine terminal pressure or opposing it. It is difficult to perceive exactly what does happen when the effect of armature reactions at some critical point, evidently on a leading power factor, predominates over the armature self induction and resistance so as to assist the machine in generating a terminal pressure greater than that upon the circuit. Such, however, is actually the case as shown by the data obtained under actual test.

In order to make clear what new relation of vectors must hold after passing this critical point, a few diagrams will serve to show the argument which was followed in arriving at the conclusions made use of in the calculation of the synchronous impedance upon leading power factors.

FIG. B

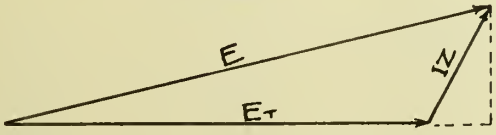
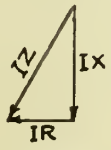


FIG. A.



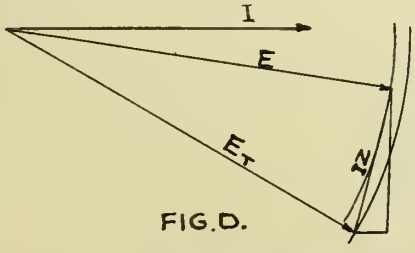


FIG. D.

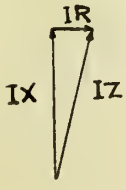


FIG. C.

If, in figure A, I R represents the resistance drop as a directive quantity, opposing the terminal pressure as shown by the arrows. In order that the resultant of I R and I X shall oppose the terminal pressure, I X which is the larger quantity must have the direction ascribed by the arrow. Then in order to arrive at the open circuit pressure, this vector I Z must

be reversed in direction and compounded with the terminal pressure. This open circuit pressure is the sum of the available terminal pressure and the pressure dissipated or obliterated within the armature. When the resultant of synchronous reactance and resistance volts assists the terminal pressure, it must be added to the open circuit pressure or subtracted from the terminal pressure under load. Thus in figure C, the components, resistance and reactance volts must assume the direction indicated in order that the resultant, I Z, may assist the terminal pressure. Fig. D, represents the method of compounding, which will result in the phasing of the several vectors properly.

DESCRIPTION OF ALTERNATOR.

The majority of the tests were made upon an inductor alternator in the Electrical Engineering Laboratory. This machine was constructed in the University shops and is rated at 7½ K.W. It has two armature windings, which if connected in parallel generate a pressure of 110 volts, and 220 volts if connected in series. The machine has 10 poles and was designed for a frequency of 60 cycles per second, which fixes the normal speed at 720 R. P. M. The full load current at 110 volts is 68 amperes. A 15 H. P., 220 volt, Westinghouse motor is belted to the alternator. A search coil of 10 turns, for finding the actual generated armature pressure was superimposed on the armature winding, spanning one polar arc.

A mil-ammeter with a suitable resistance in series, was connected in the circuit with this test coil. The ratio of the mil-ammeter readings, to the open circuit pressures of the machine, for several value of field excitation, was tested and found to be constant. By multiplying the mil-ammeter readings by this quantity the volts generated withnthe armature under load could be determined.

DESCRIPTION OF SHORT CIRCUIT TESTS.

Two short circuit tests were made with as much precision as possible. The field was first magnetized by exciting it to considerable above normal and then the excitation gradually cut down to zero. Care was taken not to exceed the value of field current desired for increasing armature currents on short circuit. A stove pipe rheostat was used to obtain a fine gradation of field current. This is a special form of rheostat in which the whole resistance is always across the line and a sliding contact admits as much resistance as desired in multiple with the remainder of the circuit. (See diagram of connections page 45 .) The alternator was kept up to speed thruout the test and all the instruments were corrected from their calibration curves.

The data is recorded in tables I & II, p 38 .

DESCRIPTION OF TESTS ON NON-INDUCTIVE LOADS.

BY E. M. F . METHOD.

CONSTANT TERMINAL PRESSURE:

The first test by the E.M.F. Method was taken for non-inductive loads from zero to 25% overload; the field excitation being increased to maintain the terminal pressure nearly constant. This non-inductive loading was obtained by using incandescent lamps as load. A rheostat in the motor field, enabled the speed to be varied as desired. A stove pipe rheostat in the field of the alternator permitted a fine adjustment of field excitation. The same care as regards increasing and decreasing the field excitation was observed in these tests as in the short circuit tests. A wattmeter measured the load on the machine and an ammeter the current flowing. The terminal pressure was measured by a voltmeter immediately at the terminals of the machine. The diagram, page, 45 , shows the connections used. Readings of terminal pressure, actual generated armature pressure, power, armature current, field current and speed were observed for each change in load. The open circuit pressures for the corresponding field currents were then observed. The magnetization curve was constructed and the open circuit voltage checked with the values from the curve. The synchronous impedance drop and working impedance drop were found for each case by means of the graphical construction and the synchronous impedance and working impedance calculated. The data for this test will be found in Tables II

and III, pages 39 + 40

CONSTANT FIELD EXCITATION:

Exactly the same apparatus and connections were used in this test as in the previous one; the only difference being that the field excitation was kept constant, while the load was decreased from 25% over load to zero. Particular care was taken to maintain synchronous speed throuout the test.

Readings of terminal pressure, actual generated armature pressure, power, field excitation and speed were observed for each change in load. The open circuit pressure for the corresponding field current was found and the synchronous impedance and working impedance drops found graphically and the two impedances calculated. The data for this test will be found in Table IV page 41.

DESCRIPTION OF TEST BY E. M. F. METHOD UNDER VARIABLE POWER FACTOR.

The inductor alternator was brought up and maintained at synchronous speed by means of a rheostat in the motor field. A stove pipe sheostat in the alternator field allowed a close adjustment of field current. The field was magnetized to above normal and the excitation gradually cut down to zero and then up to normal, care being taken not to exceed the point desired. The power was measured by a wattmeter, then terminal pressure immediately at the terminals with a voltmeter and the actual generated armature volts by the milammeter. When up to speed and normal voltage, the machine was synchronized with a 440 volt, 45 K. W. alternator. To do this it was necessary to transform the 110 volts terminal pressure of the inductor alternator to 440 volts. The driving force on the 45 K. W. alternator was then removed and the inductor alternator allowed to drive it as a synchronous motor. The connections are shown in the diagram, page 47 .

Readings were taken of power, current, field current, terminal volts, actual generated armature pressure and speed. The corresponding open circuit pressures for the various field currents were found for various power factors, both leading and lagging. When the motor field was over excited, a leading power factor resulted and a lagging power factor when under excited. Better results might be expected if the field adjustment could be accomplished entirely with the rheostat in the field of the 45 K. W. machine, but the rheostat was not

finely enough divided to make this possible. Another difficulty occured in reading the instruments correctly, due to hunting action between the two machines. All the readings were corrected by their calibration curves. The synchronous impedance and working impedance drops were found graphically and the values of working impedance and synchronous impedance calculated. The data on this experiment will be found in Table V, page 42 .

CALCULATIONS.

For the calculation of the results of the foregoing tests, a large chart was constructed, such that a volt was represented on the scale by 1/5 of an inch. The construction for unity power factor is illustrated by fig. 4, page 27. From a point O as a center, an arc was struck with a radius of 22 inches, representing to the scale of 1/5 of an inch to a volt, the normal pressure of the machine used or by scale of 1/20 of an inch, a normal pressure of 440 volts, distinguished in the following diagram by the color, red. Other arcs were struck from the same center with radii representing other pressures above and below the normal pressure and intervening arcs representing fractions of a volt. The horizontal line O.M. was made to define the direction of the current vector and also the direction of the terminal pressure for unity power factor. Taking the data reading 3, Table II the terminal pressure E_T of 112 volts was laid off on the horizontal axis and from its terminus the I R drop of .6 volts obtained from the curve Plate II, for the armature current as here illustrated, somewhat exaggerated. A perpendicular from the end of this vector was then erected to its intersection with the arc defining the open circuit pressure E. of 115.6 volts and the vector I Z_{syn} measured and its value 26.3 divided by the current 11.3 giving a value of 2.33 ohms for synchronous impedance. The vector I Z_{syn} defined by the intersection of the vertical with the arc of the armature generated volts

E_a

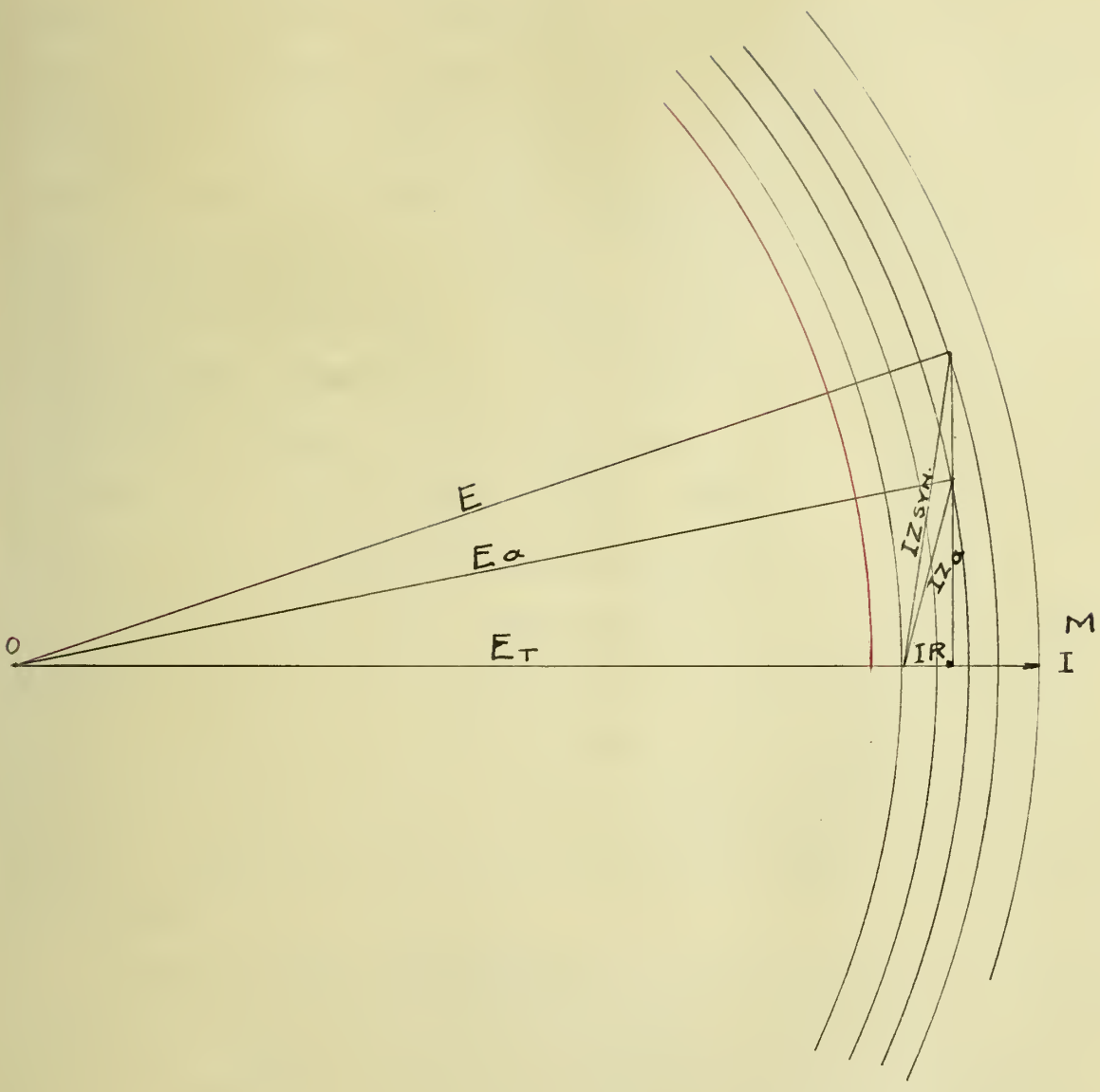


FIG. 4.

, equal to 114.3 volts; thus measured gave 19.6, which divided by the current gave a working impedance of 1.74 ohms.

For inductive and capacity loads the chart was somewhat modified to afford a convenient method of selecting the direction of the terminal pressure vector E_T. see fig. 5, page 29. The radius of the normal terminal voltage circle, along the current axis was divided into one hundred equal parts and points projected up to the arc. From these intersections radial lines were drawn, cutting the arc, and on these lines the per cents power factor were marked as defined by the per cent of the radius measured from the center on the horizontal projection of these intersections. Taking the power factor as obtained by dividing the watts by the volt amperes and locating the radial line representing that per cent and its intersection with the arc, defining the terminal pressure E_T, the I R drop was laid off in phase with the current and the vertical erected as before to its intersection with the circles representing E and E_a and the vectors I Z_{SYN} and I Z_a measured as before.

Figures 6 and 7 will illustrate the calculation of readings no. 1 and no. 5, Table V under leading power factors. Fig. 6, shows the synchronous impedance vector I $Z_{SYN.}$ lying on the opposite side of the I R drop vector from that of the working impedance, vector I Z_a. This indicates a negative synchronous impedance as referred to the direction of the actual impedance as positive. Fig. 7 illustrates the calculation of reading no. 5 in which the synchronous impedance vector I $Z_{SYN.}$ lies on the same side of the vector I R as the working impedance vector I Z_a, indicating positive synchronous impedance.

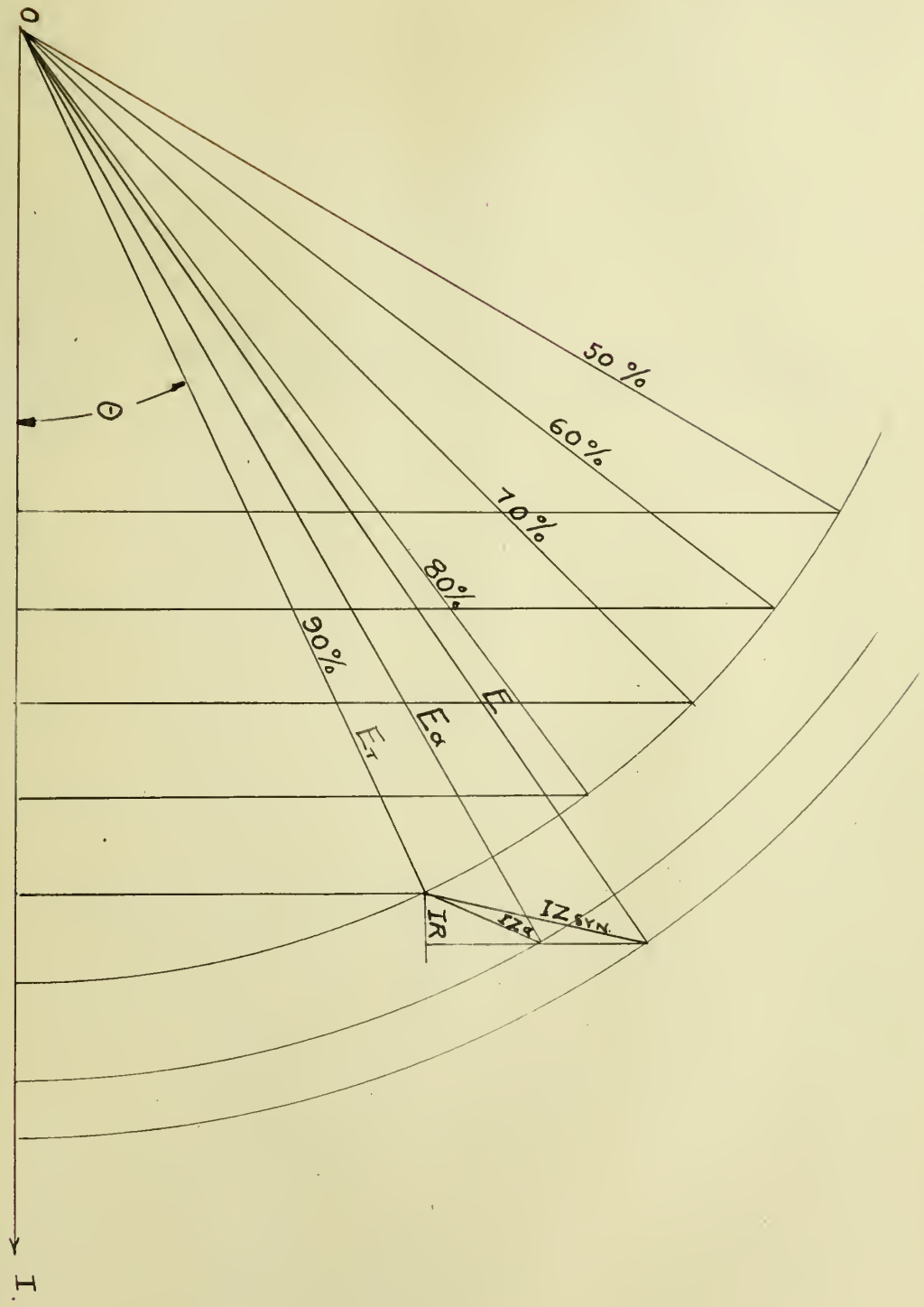


FIG.5.

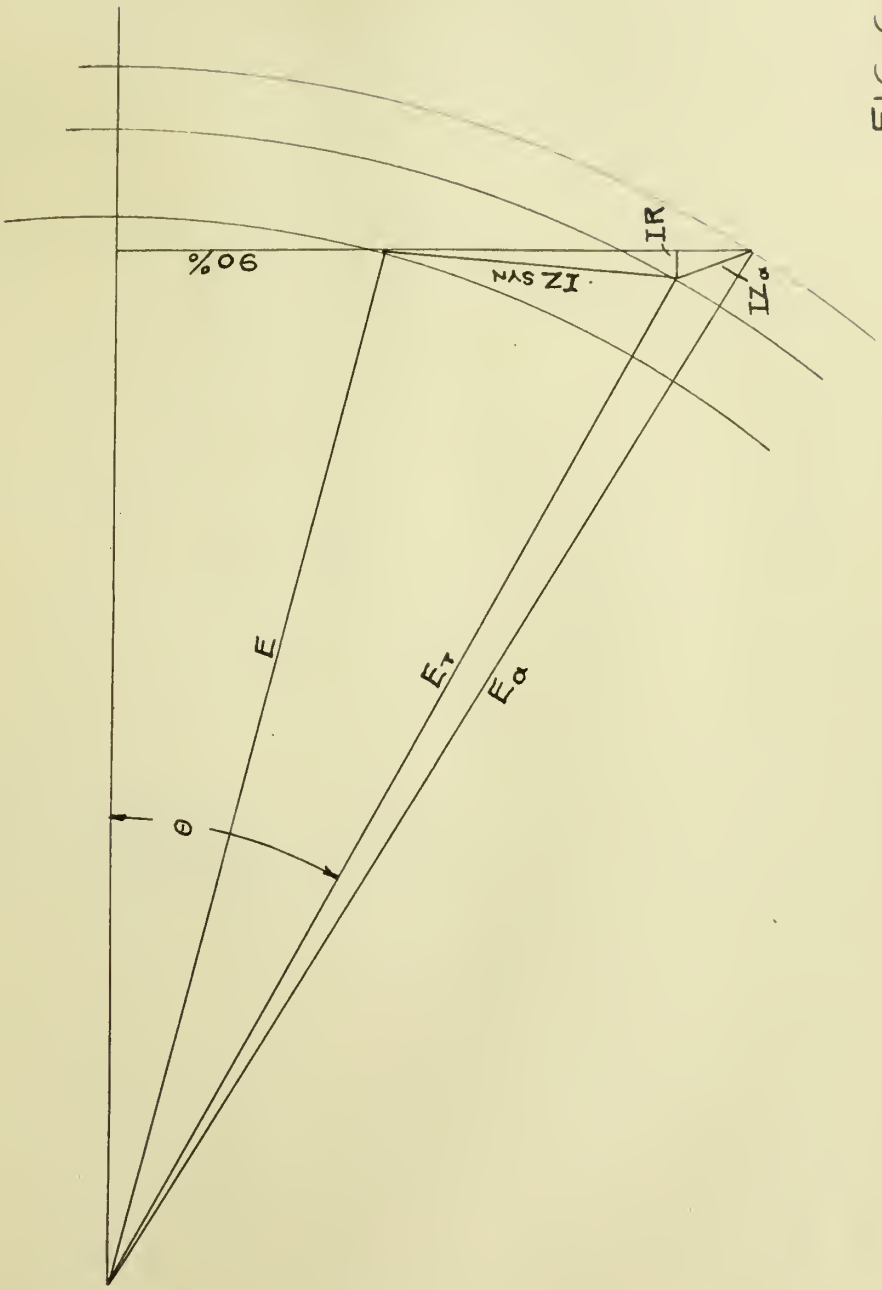


FIG 6.

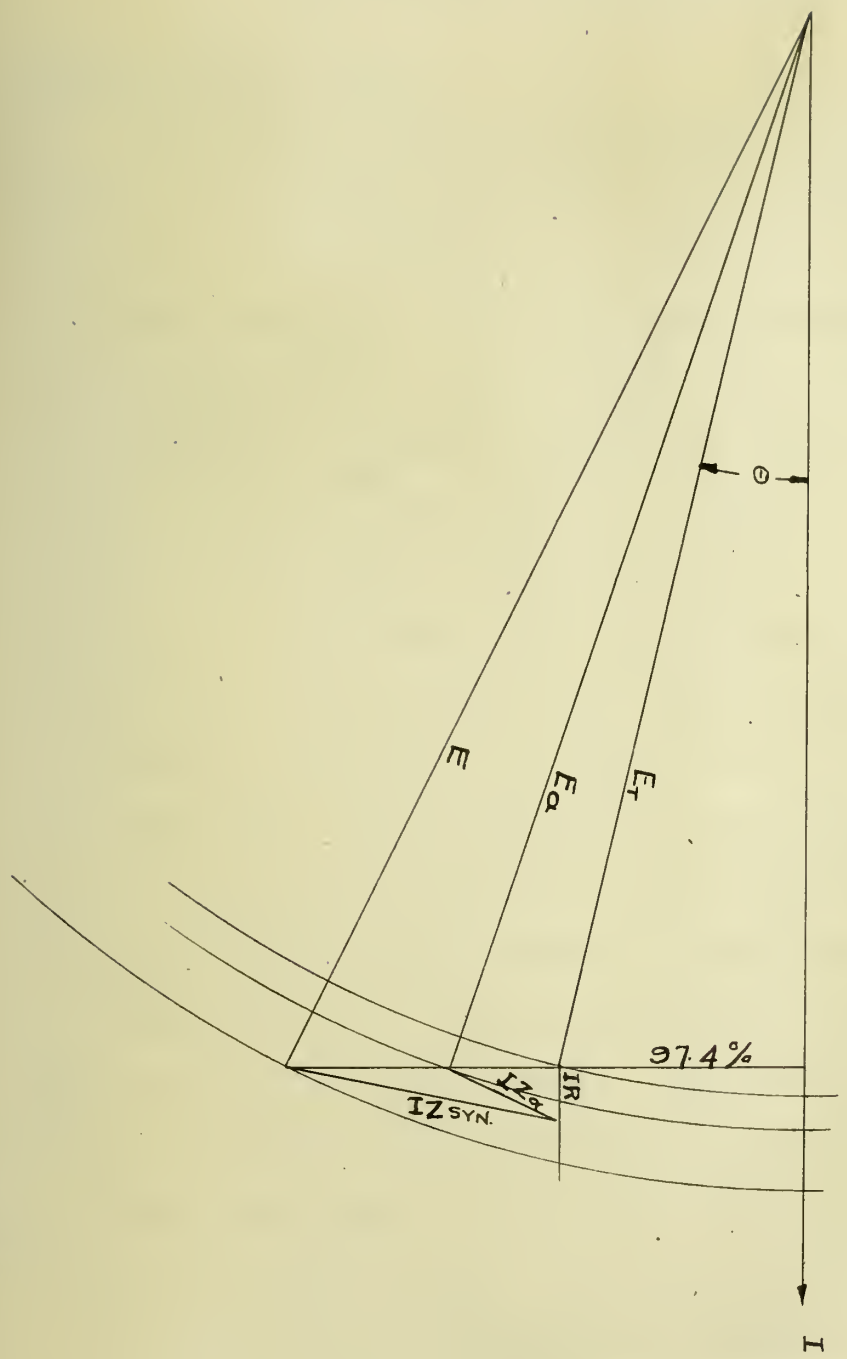


FIG 7.

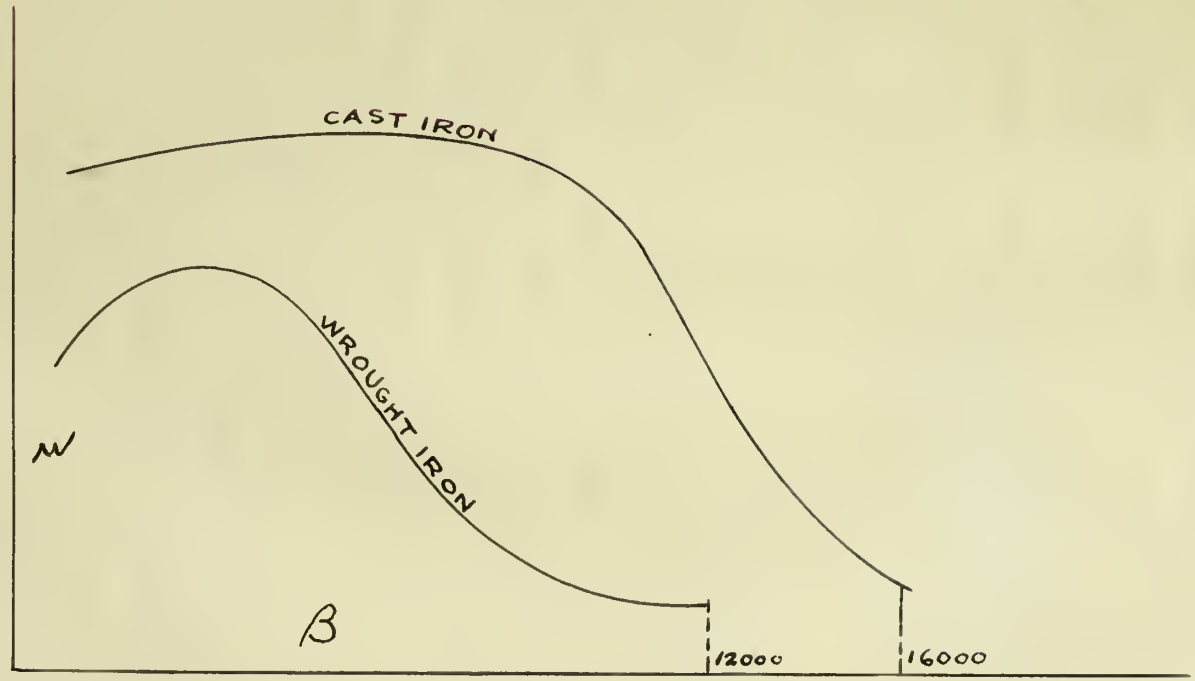
DISCUSSION OF DATA AND RESULTS.

SHORT CIRCUIT TESTS:

In the calculation of the results of the short circuit test on the inductor alternator, the corrected value of open circuit terminal pressures were divided by the corresponding armature currents. The results are summarized in Tables I & II and plotted in the form of curves with armature currents as abscissae, and values of synchronous impedance as ordinates. As will be seen by the curves the values of synchronous impedance for small armature currents exceeded those for larger currents. The value thus obtained show quite close agreement in the two tests and the same characteristic higher value on low value of current. The higher value of permeability of the iron upon a low field flux thru the armature which constitutes a part of the path of the local leakage flux might, together with the high value of armature reactions, which are a consequence of the large angle of currnet lag, may in part account for the higher value. The permeability curve of cast iron of which the armature is constructed, reaches its critical point much sooner with increase of flux than the curve for wrought iron. The results of this test are of most value as a comparison with those obtained by the E. M. F. Method. They show a value quite constant for currents from a quarter load current to above full load, which covers ordinary working conditions, but take into account only one power factor and can give no criterion of what variation might be expected with a different power factor than that of the local circuit.

NON-INDUCTIVE LOAD CONSTANT TERMINAL PRESSURE AND SPEED:

The results of the tests of the inductor alternator upon non-inductive loads and practically constant terminal pressure and speed are tabulated in Tables III & IV, and plotted on the corresponding number, show synchronous impedance as measured br the E.M.F.method is not a constant value. It is higher for small values of armature current and approaches a straight line or constant value upon large loads. The results of the short circuit method are plotted together with the E.M.F.method on each of these plates and shows a marked agreement of values above one half full load current. Contrary to the common supposition that for small armature currents the overly large value of armature reactions with the low field excitations in the short circuit test will give too large a value of synchronous impedance, the E.M.F.method shows still larger values for the same armature currents. The cause of these large values of synchronous impedance upon small loads is evident from Plate III, showing the working impedance of the armature to be higher for low values of armature current; thus becoming the predominating factor even exceeding the short circuit value of synchronous impedance. The working impedance of the armature depends to a marked degree upon the saturation of the iron. As a field flux is increased to give normal terminal pressure and large values of armature current, the value of working impedance falls off with the permeability of the iron and assumes nearly a constant value for large armature currents. For large armature currents the armature interference at unity power factor increases slightly as shown by the relative difference in the ordinate of the working and synchronous impedance for certain armature currents. The variation of coefficient of selfinduction of the armature agrees



$$L = \frac{4\pi \mu S N^2 i}{l}$$

with the following equation approximately, hence is greatly dependant upon the permeability of the iron.

$$L = \frac{4\pi\mu S N^2}{l} \quad \text{or} \quad L = K\mu$$

CONSTANT FIELD EXCITATION:

With constant excitation under the regulation test the values of working impedance remained more nearly constant in value, than under the other tests as shown by Plate IV. This might be explained in part by the fact that since the saturation of the field remained practically constant, the working inductance would be subject to less variation; a fact also borne out by the curve of working impedance. It is a noticeable fact that synchronous impedance and working impedance curves are nearly parallel, indicating a practically constant value of armature interference.

VARIABLE POWER FACTOR:

The data taken upon this test was not as complete as might be desired for reaching definite conclusions. The curve of synchronous impedance on Plate VI, shows both positive and negative values. For power factors of 80 to 85 % the values of synchronous impedance are higher than those for a similar load at unity power factor. The trend of the curve from points shown seems to indicate an increasing value of synchronous impedance with an increase of the angle of the lag. For leading current the synchronous impedance decreases slowly to about 97% power factor, where it reaches the value of the armature resistance, at which point, it is probable a state of resonance exists. For power factor lower than 90% the synchronous impedance increases in value not as an interference but a factor assisting the regulation of the machine.

The values of working impedance of the armature for a leading current reduce to approximately the resistance of the armature, tending to remain constant as shown by the four points between 77 and 90% power factor. From 97 to 100% a marked increase is shown; the values for a lagging power factor showing a slight decrease with increased angle of lag.

More nearly ideal conditions for measuring synchronous impedance under variable power factor would have been attained by maintaining a constant armature current, and constant field excitation on the alternator. Such a condition could be attained only by having a flexible load and a finely divided rheostat in the motor field. The writers are of the opinion that machines designed to regulate on lagging power factors below 20% or for zero power factor will best fulfill the requirements of service conditions.

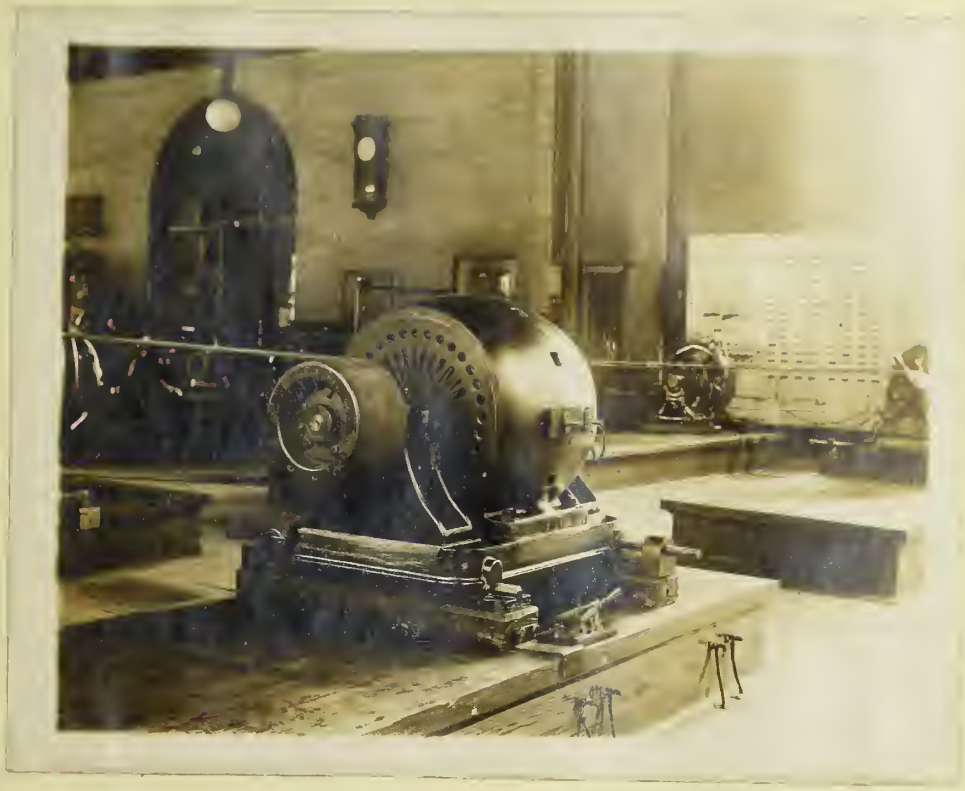
DESCRIPTION OF TESTS ON A 120 K. W. Alternator.

This machine was a 440 volt, two phase, Westinghouse alternator, direct connected to a compound Westinghouse engine. A search coil of six turns was superimposed over a portion of the winding of one phase on the stationary armature. This winding was distributed rather than concentrated in one slot. A short circuit test on one phase was made and the synchronous impedance calculated from the data, Table VI, page 43.

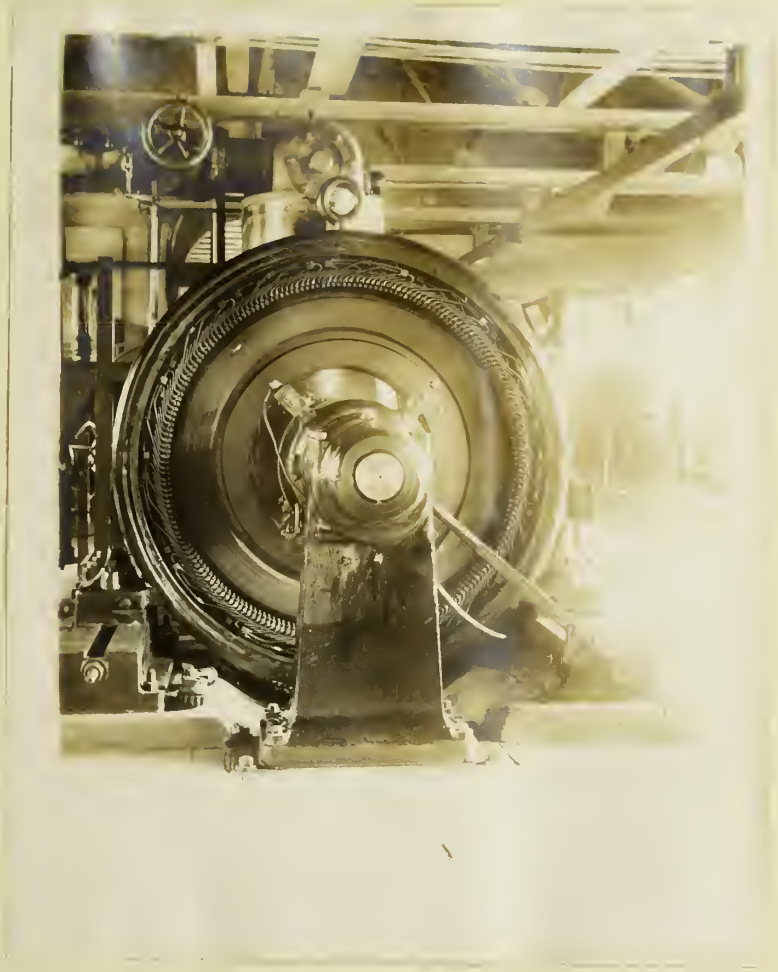
A test by the method of balancing external resistance and armature impedance was made and the impedance found from data in Table VII page 44.

Two tests were run in order to find the synchronous impedance by the E. M. F. method. One set of readings was taken late at night when the motor load was off and the load was nearly noninductive. Another set was taken thru the day, when the power factor was lower on account of inductive load. Readings were taken for various power factors and the results of these two tests proved worthless because the speed of the machine could not be maintained, there being a variation of 10%. Another great trouble was the variation in load and the unreliability of the instruments used in the determination of power factor. The exhaust steam from the engine which is direct connected to the alternator is used for heating and change in back pressure affects the engine speed; this trouble could be overcome by mounting a tachometer on the shaft so that simultaneous readings of speed and pressure could be taken. The variation in load cannot be remedied however, and

this is the chief objection to the usefulness of this method under actual power plant conditions. A short circuiting switch was placed in the ammeter and wattmeter circuit so that the instruments could be cut out when not in use. The connections are shown on page 47.



7½ K.W. INDUCTOR ALTERNATOR



WESTINGHOUSE, 120 K.W. ALTERNATOR

TABLE I

SHORT CIRCUIT TEST
INDUCTOR ALTERNATOR

TEST 1.

FIELD CURRENT AMPERES	OPEN CIRCUIT PRESSURE VOLTS	ARMATURE CURRENT AMPERES	FREQUENCY CYCLES	SYNCHRONOUS IMPEDANCE OHMS
.05	4.1	3.0	60	1.65
.10	11.2	12.5	60	.90
.15	15.7	16.1	60	.976
.20	20.3	21.5	60	.943
.25	25.0	25.6	60	.975
.30	30.2	31.4	60	.960
.37	35.5	36.6	60	.960
.40	37.4	38.5	60	.970
.45	43.4	44.6	60	.970
.50	47.0	48.3	60	.972
.55	51.9	53.5	60	.994
.60	58.7	61.0	60	.970
.65	61.5	63.7	60	.962
.70	65.2	67.6	60	.966
.75	69.8	72.1	60	.964
.80	74.0	76.5	60	.967
.85	78.5	81.0	60	.970
.90	83.5	86.2	60	.967

TEST 2.

FIELD CURRENT AMPERES	OPEN CIRCUIT VOLTS	ARMATURE CURRENT AMPERES	FREQUENCY CYCLES	SYNCHRONOUS IMPEDANCE OHMS
.10	12.5	10	60.3	1.25
.15	16	14	60.3	1.14
.20	20	18.4	60.3	1.085
.25	26	23.7	60.3	1.098
.30	28.2	28.1	60.3	1.005
.375	35.2	34.8	60.3	1.01
.40	37.2	37.1	60.3	1.00
.45	42.2	42.2	60.3	1.00
.50	46.4	45.9	60.3	1.01
.55	50.3	50.7	60.3	.994
.60	55.7	56.2	60.3	.99
.65	59.3	60.3	60.3	.98
.70	62.9	65.3	60.3	.962
.75	67.2	68.4	60.3	.982
.80	71.5	74.4	60.3	.964

TABLE II.

NON-INDUCTIVE LOAD TEST BY E.M.F. METHOD
INDUCTOR ALTERNATOR.
CONSTANT TERMINAL PRESSURE

FIELD CURRENT AMPERES	OPEN CIRCUIT PRESSURE VOLTS	TERMINAL PRESSURE VOLTS	ARMATURE GENERATED PRESSURE VOLTS	ARMATURE CURRENT AMPERES	POWER WATTS	FREQUENCY CYCLES	ARMATURE RESISTANCE DROP VOLTS	WORKING IMPEDANCE DROP VOLTS	SYNCHRONOUS IMPEDANCE DROP VOLTS	WORKING IMPEDANCE OHMS	SYNCHRONOUS IMPEDANCE OHMS
1.35	111.8	110.3	110.3	3.3	380	60	.18	23.6	12.7	7.14	3.82
1.40	114.0	111.3	111.9	6.3	740	60	.35	44.9	26.4	7.14	3.82
1.40	114.0	110.5	112.9	9.15	1070	60	.53	17.6	26.4	1.92	2.89
1.45	115.6	112.0	114.3	11.3	1300	60	.66	19.6	26.3	1.74	2.33
1.45	115.6	110.7	112.4	16.3	1840	60	1.00	13.3	30	.818	1.84
1.45	115.6	109.8	111.3	20.75	2290	60	1.25	10.3	33	.498	1.59
1.50	118.2	110.2	113.4	24.70	2780	60	1.53	19.2	38.5	.778	1.56
1.55	121.1	110.4	113.7	29.25	3300	60	1.82	19.0	45.7	.650	1.56
1.58	125.3	113.0	115.3	29.25	3370	59.8	1.82	11.2	50.6	.383	1.73
1.60	121.5	113.3	116.9	34.55	4010	59.8	2.16	10.9	38.1	.316	1.10
1.60	121.5	112.2	116.2	37.95	4370	59.8	2.37	19.7	40.5	.519	1.07
1.60	121.5	110.8	114.6	42.30	4780	59.8	2.67	16.9	43.5	.301	1.03
1.60	121.5	109.9	113.4	45.15	5070	59.8	2.85	13.6	45.7	.301	1.01
1.70	126.2	111.5	116.5	48.05	5451	59.8	3.01	21.4	53.2	.446	1.10
1.70	126.2	109.7	115.2	52.15	5761	59.8	3.29	22.9	56.7	.439	1.08
1.75	127.6	109.8	115.4	56.70	6180	59.8	3.57	21.7	58.8	.383	1.03
1.85	134.5	113.2	119.8	63.70	7800	59.7	3.90	26.6	66.4	.418	1.04
1.85	134.5	111.8	118.8	67.05	7480	59.7	4.22	26.2	68.0	.391	1.01
1.87	134.7	111.4	118.8	70.25	7720	59.7	4.40	27.1	69.1	.387	.987
1.87	134.7	109.9	117.9	73.35	8010	59.7	4.63	26.3	71.0	3.59	.968
2.00	138.9	111.7	119.8	78.80	8720	59.5	4.95	28.70	75.6	3.68	.970
2.00	138.9	111.1	119.9	81.10	8930	59.5	5.12	27.90	76.0	3.44	.936

TABLE III

NON-INDUCTIVE LOAD TEST BY E.M.F METHOD
INDUCTOR ALTERNATOR
CONSTANT TERMINAL PRESSURE

FIELD CURRENT AMPERES	OPEN CIRCUIT PRESSURE VOLTS	TERMINAL PRESSURE VOLTS	ARMATURE GENERATED PRESSURE VOLTS	ARMATURE CURRENT AMPERES	POWER WATTS	FREQUENCY CYCLES	ARMATURE RESISTANCE DROP VOLTS	WORKING IMPEDANCE DROP VOLTS	SYNCHRONOUS IMPEDANCE DROP VOLTS	WORKING IMPEDANCE OHMS	SYNCHRONOUS IMPEDANCE OHMS
2.0	140	111.5	120.1	79.5	8620	59.6	5.00	29.8	780	.375	.982
1.68	126	110.3	117.0	51.8	5800	59.6	3.25	28.9	55.2	.558	1.065
1.60	123	110.3	115.5	42.7	4900	59.6	3.00	25.4	51.0	.595	1.36
1.49	117.8	110.0	114.8	34.0	3870	59.6	2.11	25.6	37.0	.752	1.09
1.47	116.7	110.3	114.3	29.5	3350	59.6	1.85	22.3	32.5	.756	1.10
1.49	117.8	111.2	114.3	25.8	2920	59.6	1.60	22.3	36.2	.874	1.40
1.49	117.8	110.2	112.4	17.5	1960	59.6	1.05	15.5	38.8	.885	2.22
1.49	117.8	111.2	113.1	12.7	1420	59.6	.75	16.8	37.3	1.32	2.94
1.49	117.8	110.1	111.7	8.7	1000	59.6	.50	16.0	41.0	1.84	4.72
1.48	117.6	110.5	111.7	6.5	760	59.6	.35	15.2	39.9	2.34	6.15

TABLE IV.

NON-INDUCTIVE LOAD TEST BY E.M.F METHOD
INDUCTOR ALTERNATOR
CONSTANT FIELD CURRENT

OPEN CIRCUIT PRESSURE VOLTS	TERMINAL PRESSURE VOLTS	ARMATURE GENERATED PRESSURE VOLTS	ARMATURE CURRENT AMPERES	POWER WATTS	FREQUENCY CYCLES	ARMATURE RESISTANCE DROP VOLTS	WORKING IMPEDANCE DROP VOLTS	SYNCHRONOUS IMPEDANCE DROP VOLTS	WORKING IMPEDANCE OHMS	SYNCHRONOUS IMPEDANCE OHMS
134	110.8	119.4	68.8	7620	59.8	4.38	32.1	69.0	.466	1.001
134	112.6	121.0	65.6	7300	59.8	4.12	32.3	65.8	.493	1.001
134	115.5	124.7	59.8	6920	59.8	3.77	36.7	61.3	.615	1.027
134	118.1	124.7	53.4	6880	59.8	3.37	27.8	56.5	.522	1.058
134	121.2	126.6	45.3	5660	59.8	2.86	26.2	50.9	.579	1.123
134	123.8	129.0	37.5	4830	59.8	2.35	27.9	46.0	.744	1.226
134	125.7	129.7	33.6	4400	59.8	2.10	23.1	41.1	.688	1.225
134	127.5	131.8	28.9	3800	59.8	1.82	26.2	35.0	907	1.212
134	130.7	132.8	20.0	2670	59.8	1.22	16.6	22.9	.932	1.143
134	131.7	132.8	10.5	1300	59.8	.67	10.0	19.7	.952	1.875

TABLE V

CAPACITY AND INDUCTANCE LOAD TEST BY E.M.F METHOD

INDUCTOR ALTERNATOR

FIELD CURRENT AMPERES	OPEN CIRCUIT PRESSURE VOLTS	TERMINAL PRESSURE VOLTS	ARMATURE GENERATED PRESSURE VOLTS	ARMATURE CURRENT AMPERES	POWER WATTS	POWER FACTOR	FREQUENCY CYCLES	ARMATURE RESISTANCE DROP VOLTS	WORKING IMPEDANCE DROP VOLTS	SYNCHRONOUS IMPEDANCE DROP VOLTS	WORKING IMPEDANCE OHMS	SYNCHRONOUS IMPEDANCE OHMS
1.35	111	111.8	116.8	63.0	6320	LEAD .899	59.7	3.97	5.00	-12.5	.0794	-.2450
1.25	106	109.3	114.6	6775	6550	.884	59.7	4.27	5.00	-17.6	.074	-.269
1.20	103	108.6	113.2	72.8	6730	.853	59.7	4.60	4.70	-23.0	.064	-.316
1.50	118.5	113.2	117.5	57.6	6350	.974	59.7	3.62	5.20	+8.2	.090	+.142
1.42	114.8	110	114.7	59.75	6790	1.00	59.7	3.77	1.45	+21.7	.243	+.364
1.95	138	110	117.3	31.05	3370	LAG. .986	59.7	1.94	2.14	+6.47	.690	+2.07
2.08	143	111.0	118.4	32.75	3400	.943	59.7	2.05	1.44	+5.85	.441	+1.78
1.72	128	98.7	106.6	32.75	3120	.965	59.7	2.05	1.80	+5.25	.550	+1.60
1.92	136.8	101.1	109.2	36.25	3120	.850	59.7	2.27	1.08	+5.10	.298	+1.41
1.97	138.7	101.1	109.2	36.75	3120	.840	59.7	2.30	1.10	+5.25	.298	+1.42
2.03	141.2	101.8	109.9	38.10	3180	.822	59.7	2.39	1.03	+5.53	.271	+1.45
2.04	141.7	100.6	109.2	38.6	3170	.817	59.7	2.45	.97	+5.55	.251	+1.43

TABLE VI

SHORT CIRCUIT TEST
120 K.W. ALTERNATOR

FIELD CURRENT AMPERES	OPEN CIRCUIT PRESSURE VOLTS	ARMATURE CURRENT AMPERES	FREQUENCY CYCLES	SYNCHRONOUS IMPEDANCE OHMS
.50	11.5	23.0	60	.500
1.00	16.5	31.0	60	.530
1.50	22.0	42.4	60	.520
2.00	27.9	54.1	60	.533
2.50	35.0	65.8	60	.533
3.00	40.0	76.8	60	.533
3.50	47.7	89.0	60	.535
4.00	53.1	94.8	60	.560
4.30	58.2	102.4	60	.568
4.50	62.0	107.4	60	.578
4.80	65.9	114.0	60	.577
5.00	67.0	119.6	60	.560
5.30	72.0	127.6	60	.565
5.50	76.0	130.4	60	.570
5.70	78.2	137.2	60	.570
6.10	83.0	146.0	60	567
6.40	88.0	152.8	60	.576
6.50	91.0	156.2	60	.580

TABLE VII

Comparison of Short Circuit and Resistance Balance Methods

Short Circuit Method

Field Current	Open Circuit Pressure	Armature Current	Frequency	Synchronous Impedance	Number of Reading
Amperes	Volts	Amperes	Cycles	Ohms	
4.30	58.2	102.4	60	.568	1.
3.00	40.9	76.8	60	.533	2.
2.50	35.0	65.8	60	532	3.
2.00	27.9	54.1	60	.515	4

Resistance Balance Method

Field Current	Open Circuit Pressure	Armature Current	Frequency	Total Impedance	Synchronous Impedance	Number of Reading
Amperes	Volts	Amperes	Cycles	Ohms	Ohms	
4.30	58.2	71.0	60	82	.410	1.
3.00	40.9	52.4	60	.78	.390	2.
2.50	35.0	46.0	60	.76	.380	3.
2.00	27.9	37.2	60	.75	.375	4

DIAGRAM OF CONNECTIONS
NON-INDUCTIVE LOAD TEST BY E.M.F. METHOD.
INDUCTOR ALTERNATOR.

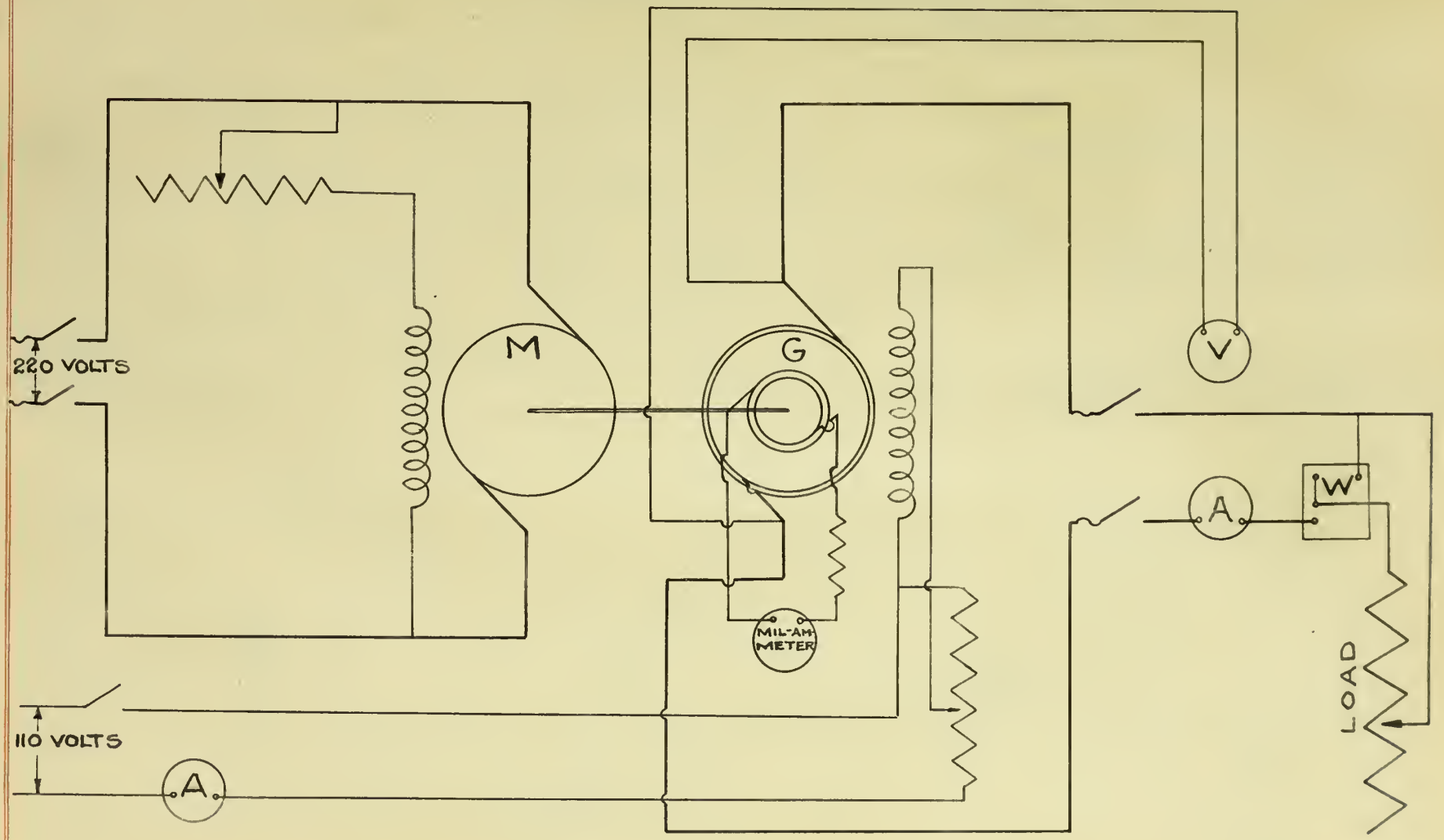


Diagram of Connections
Varying Power Factor Test by E.M.F. Method
Inductor Alternator

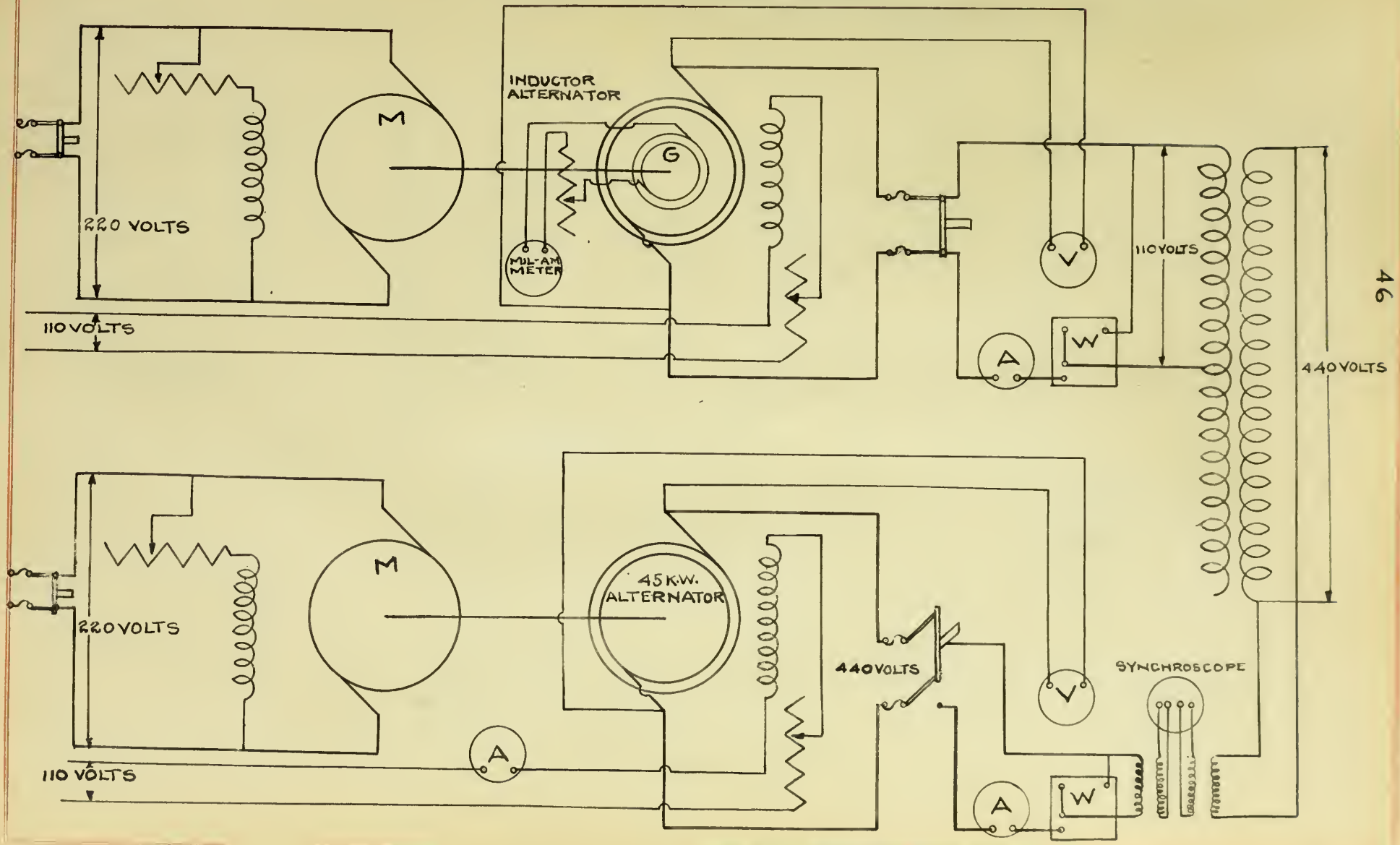
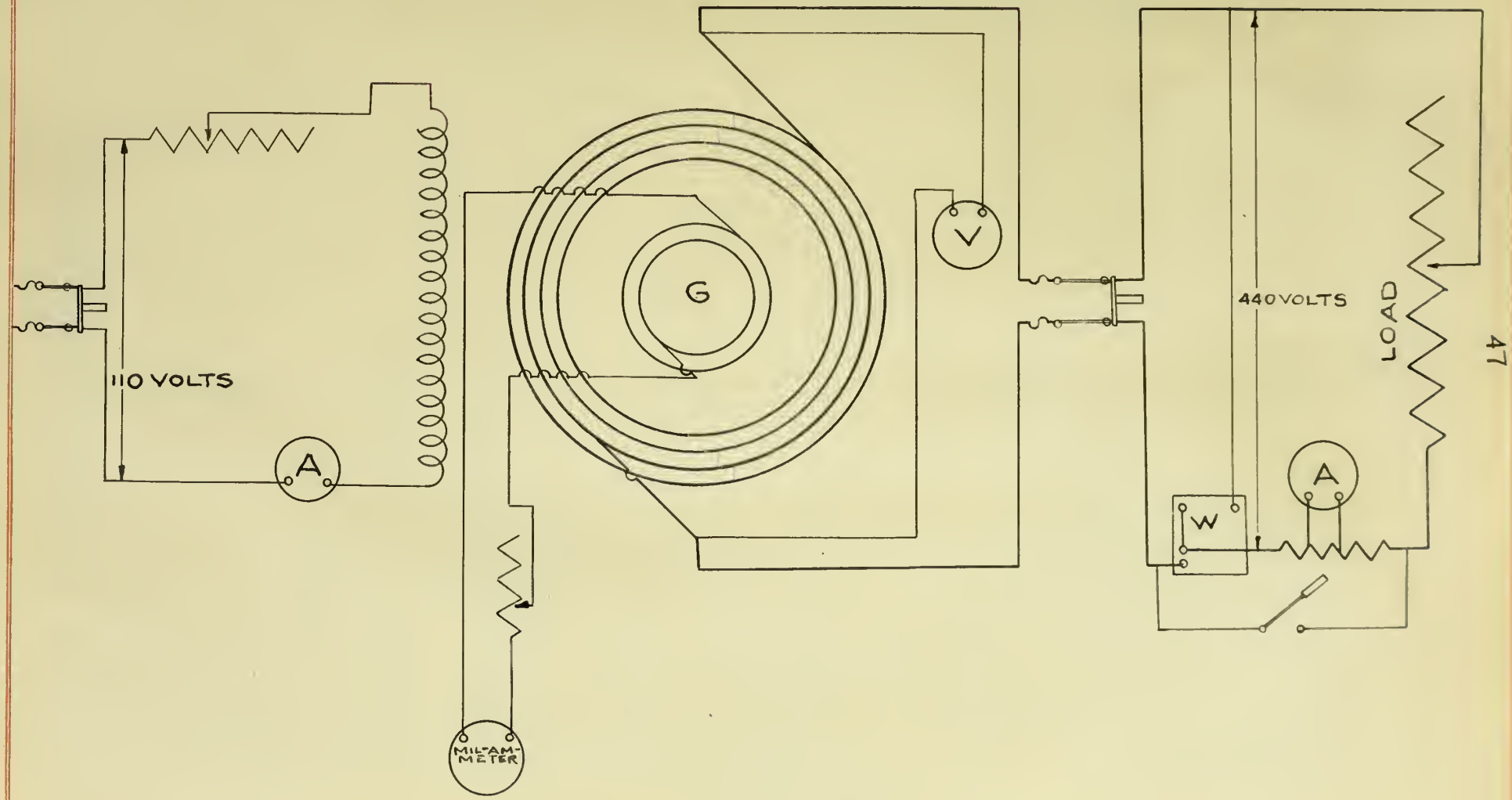


Diagram of Connections
Non-Inductive Load Test by E.M.F. Method
120 K.W. Alternator.



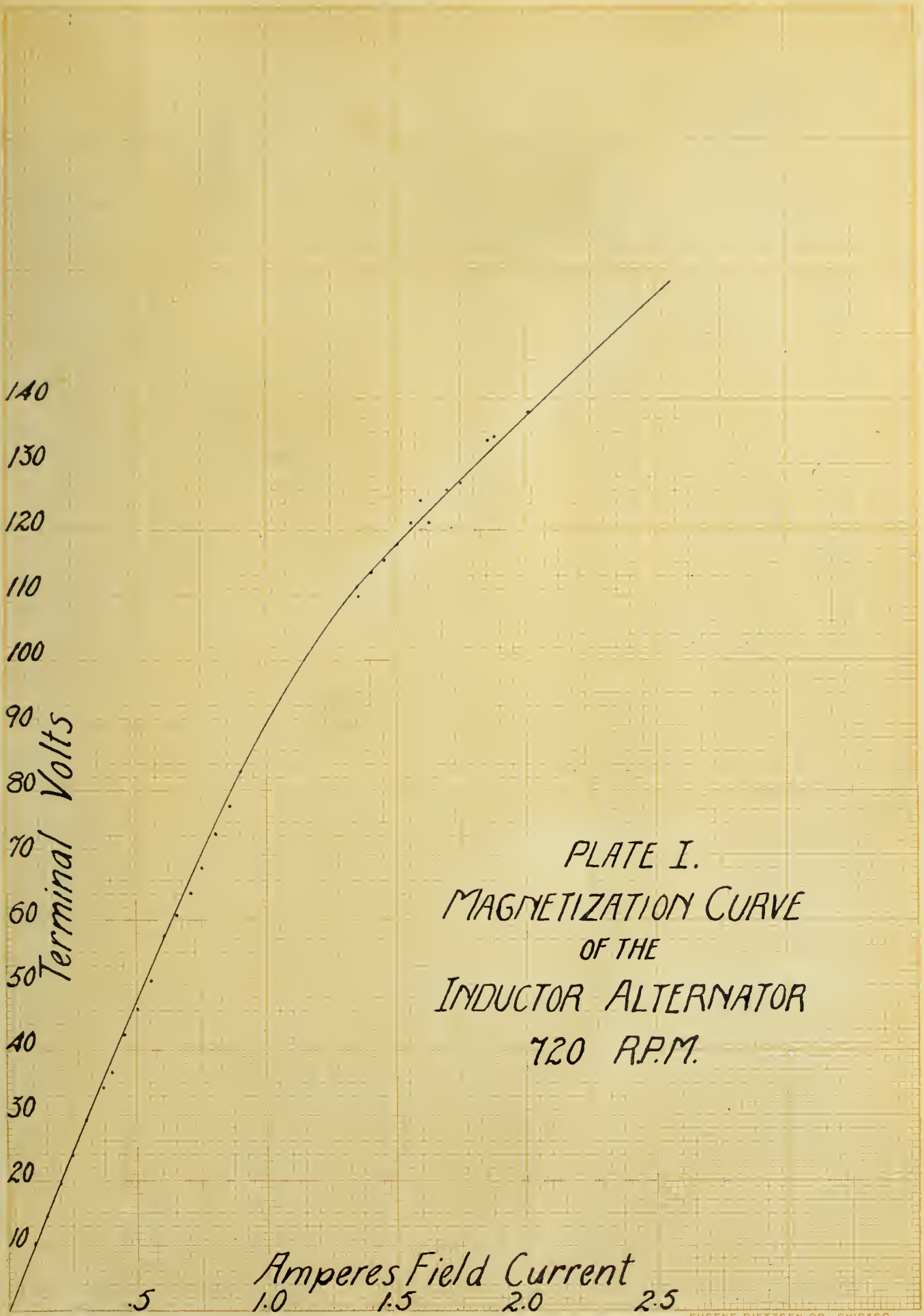


PLATE I.

MAGNETIZATION CURVE

OF THE

INDUCTOR ALTERNATOR

720 R.P.M.

EUGENE DIETZGEN CO., CHICAGO

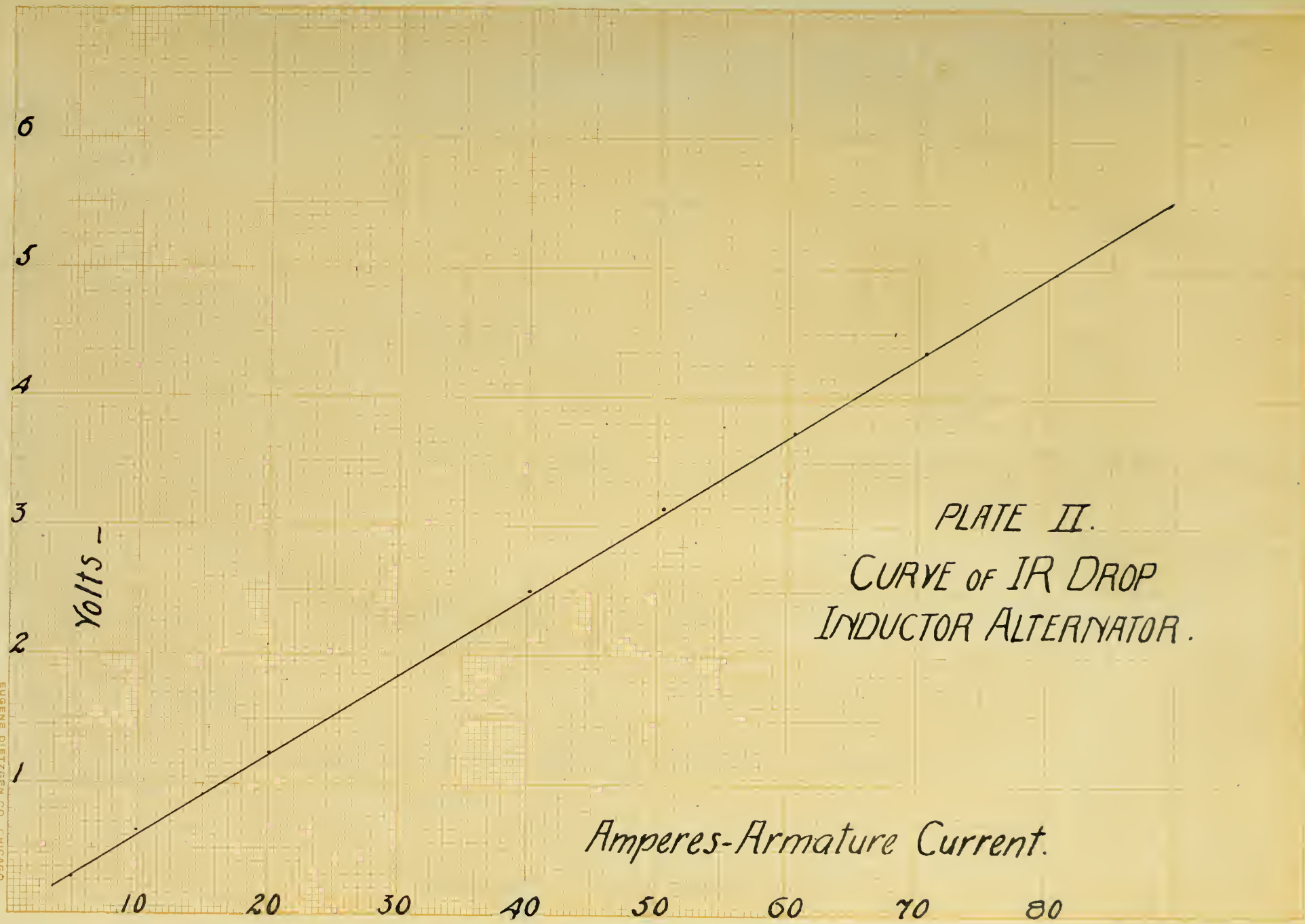


PLATE II.

CURVE OF IR DROP

INDUCTOR ALTERNATOR.

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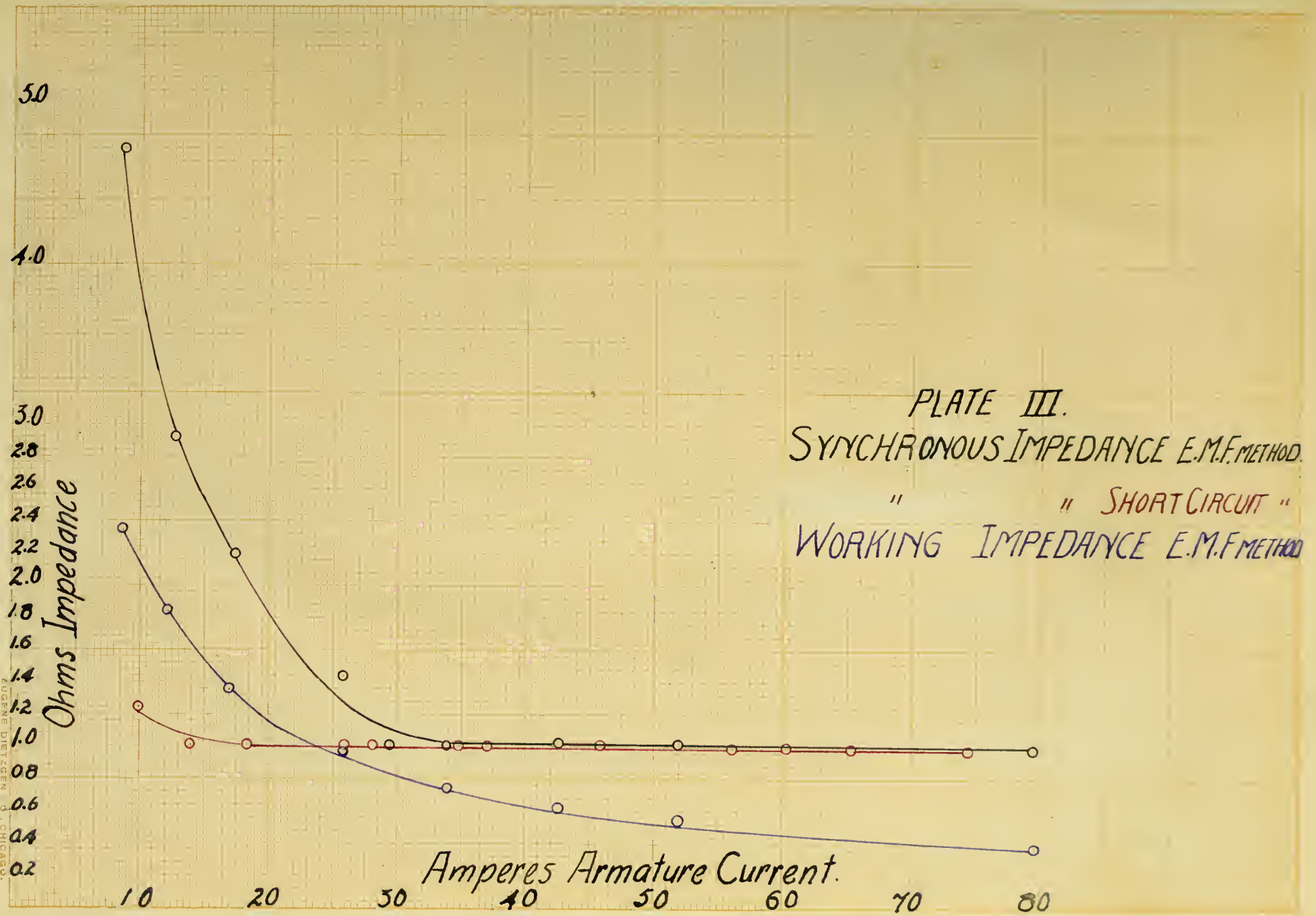
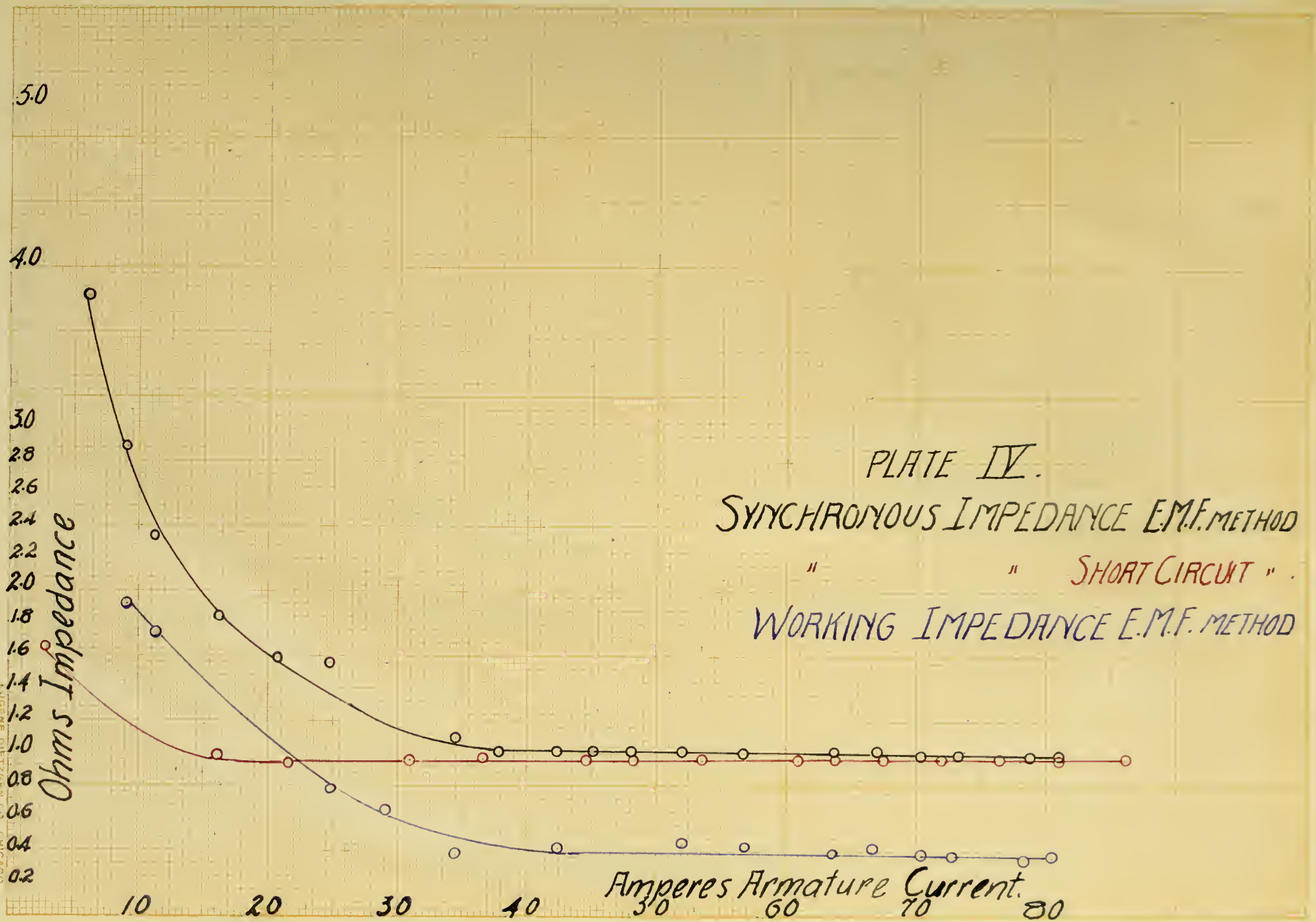


PLATE III.
SYNCHRONOUS IMPEDANCE E.M.F. METHOD.
" " SHORT CIRCUIT "
WORKING IMPEDANCE E.M.F METHOD
Ohms Impedance
5.0
4.0
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Amperes Armature Current.
10
20
30
40
50
60
70
80
EUGENE DIETZGEN CO. CHICAGO.


5.0
4.0
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Ohms Impedance
10
20
30
40
50
60
70
80
Amperes Armature Current.
PLATE IV.
SYNCHRONOUS IMPEDANCE E.M.F. METHOD
" " SHORT CIRCUIT " .
WORKING IMPEDANCE E.M.F. METHOD
EUGENE DIETZGEN CO. CHICAGO.

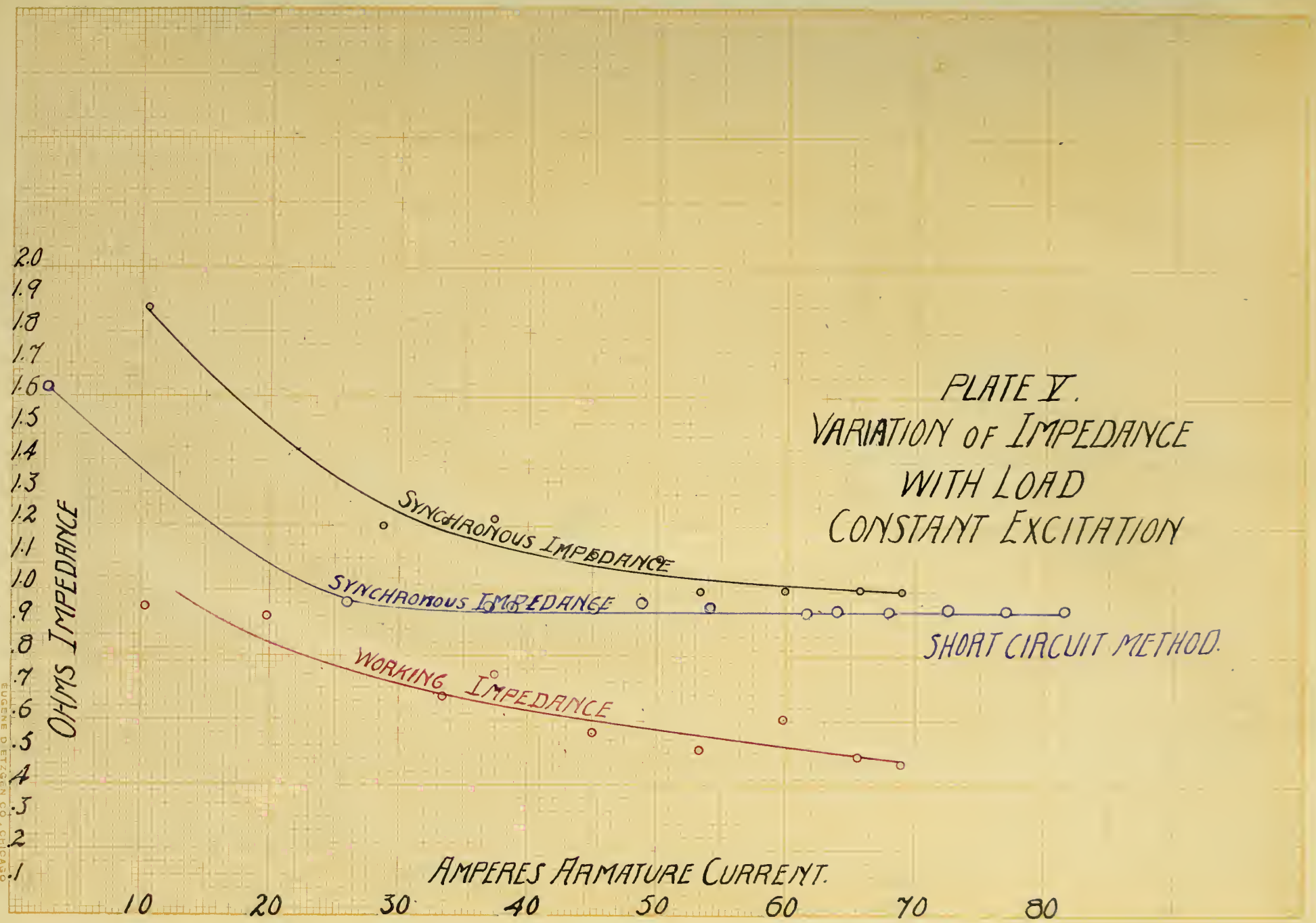


PLATE V.
VARIATION OF IMPEDANCE
WITH LOAD
CONSTANT EXCITATION
SYNCHRONOUS IMPEDANCE
SYNCHRONOUS IMPEDANCE
SHORT CIRCUIT METHOD.
WORKING IMPEDANCE
OHMS IMPEDANCE
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
AMPERES ARMATURE CURRENT.
10
20
30
40
50
60
70
80
EUGENE D ETZGEN CO. CHICAGO

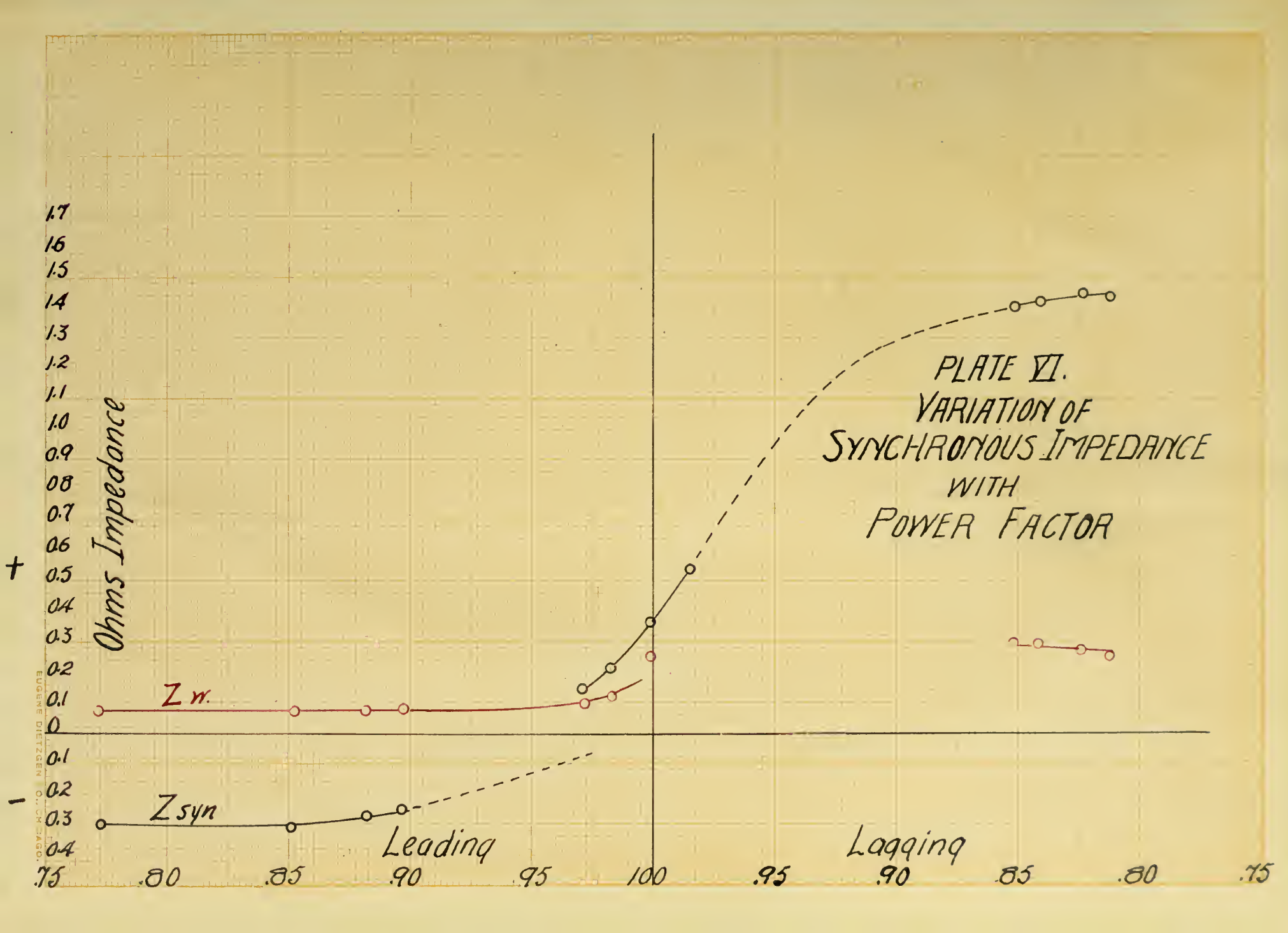


PLATE VI.
VARIATION OF
SYNCHRONOUS IMPEDANCE
WITH
POWER FACTOR
Ohms Impedance
+
−
Z w.
Z syn
Leading
Lagging
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
.75
.80
.85
.90
.95
1.00
.95
.90
.85
.80
.75
EUGENE DIETZGEN CO. CHICAGO.

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